

# Research Opportunities in Advanced Aerospace Concepts

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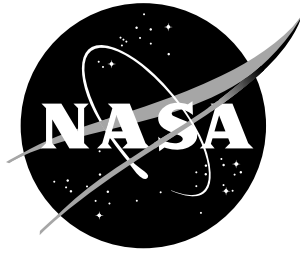
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## EXECUTIVE SUMMARY

The Aerodynamics, Aerothermodynamics, and Acoustics Competency (AAAC) formed four teams to develop white papers. The four teams were to address, respectively, Advanced Aerospace Concepts, Flow and Noise Control, Advanced Design Tools, and Hypersonic Airbreathing Propulsion Flowpath. The stated purpose of the teams was to:

- Provide a basis for an aerodynamics R&T vision for the next ten years that can be marketed both internally and externally.
- Provide a basis for developing future branch and competency portfolios consistent with the vision.
- Assist in maintaining, growing, and developing core competencies.

Each team was to address requirements for

- Physical and chemical modeling
- Computational tools
- Experimental facilities
- Instrumentation and measurements

It was further stated that performance enhancement, noise and emissions reduction, multidisciplinary integration, and certification by analysis were important considerations.

The focus was determined to be the next ten years starting with the current state of the art.

This paper documents the efforts of the Advanced Aerospace Concepts team to meet those requirements. The team decided to focus on advanced technologies, rather than catalog every unusual aircraft that has ever been attempted. The team feels strongly that individual vehicles, platforms, or airframes should be just a focus for demonstrating the benefits of technologies that can then be widely applied to many platforms. However, the team also recognizes the benefit of using the study of advanced vehicles as a tool to uncover new directions for technology development.

In order to dispel the myth that "aerodynamics is a mature science" an extensive list of "What we cannot do, or do not know" was enumerated. A zeit geist, a feeling for the spirit of the times, was developed, based on existing competency research and on previous and concurrent efforts to develop similar research goals. Technological drivers and the constraints that might influence these technological developments in a future society were examined.

The present status of aeronautics, space exploration, and non-aerospace applications, both military and commercial, including enabling technologies are discussed. A discussion of non-technological issues affecting advanced concepts research is presented. An appendix is provided containing examples of advanced vehicle configurations currently of interest.

# INTRODUCTION

Civil aviation, particularly commercial, business, and personal airplane flight, provides the finest example of why aerodynamics is incorrectly considered to be a fully mature discipline. All of the airplanes look alike; only the scale differs. The reason for this is quite simple. Like the 12-meter yachts of America's Cup sailboat racing from a few years ago, nearly all of the vehicles flying today are finely tuned examples of a single concept. Also, like the 12-meter yachts, these airplanes are exquisite masterpieces of technological development trapped in an evolutionary dead end. The limitation of the sailboat-racing world was a self-imposed one originating from the viewpoint that racing was an exercise of personal skill rather than technological prowess. In the case of current aircraft, the limitation appears to be a consequence of an inadequate design paradigm.

The essential question regarding today's aircraft is the following: **Have we actually reached a point where only incremental changes are possible, due to a restricted design space? Do we understand the physics well enough to model or change the design space for complex flows that will lead to a revolution?** The answer is no and thus the mantra of revolutionary and advanced aerospace concepts remain elusive at best.

To determine how to invest the resources of the AAAC it is important to understand where shortcomings are that influence enabling technology for revolutionary advances in aerodynamics. In this light, a list has been started to answer the following question, **with the implication that these are areas where the AAAC can and should invest in technology development:** What is it that we CANNOT DO or DO NOT KNOW in aerodynamics today? (While the list contains a wide spectrum of information, it is not meant to be all-inclusive and should be reviewed and updated as these ideas are addressed or as new ones arise.)

## **What We Cannot Do (or Do Not Do Very Well):**

- **Aircraft certification by analysis.**
  - ➔ Accurately predict aircraft performance through entire operating envelope. (limitations include safety factors, acoustics signatures, emissions, etc.)
    - ▶ Accurately predict safety factors related to maneuverability, particularly near the ground. Also cannot predict the impact of time-dependent flow control devices on aircraft performance.
    - ▶ Accurately predict configuration effects on aeroacoustic emissions and performance for revolutionary concepts (e.g. integrated aerodynamic design with accurate noise predictions).
    - ▶ Accurately predict impact of chemically reacting flows resulting in inability to determine environmental emissions



- **Accurately Predict/model/design general aircraft performance including**
  - ➔ Design capability for aircraft other than ones that are “cigar-shaped with wings” is limited due to lack of empirical methods that the current design techniques depend on.
  - ➔ If the design of an aircraft were focused on a single important revolutionary metric (e.g., zero drag, noiseless, emissionless, etc.), what would such a vehicle look like?
  - ➔ Short cycle time for designing process, allowing extensive exploration of design space.
  - ➔ Integration of CFD and CAA to accurately predict noise signatures
  - ➔ Multidisciplinary research, leading to knowledge of multidisciplinary effects and design [e.g., integration of engines, control surfaces, and other technologies (structures, materials, electronics, micro-, nano-technology, etc.)]
  - ➔ CFD and experimental measurements of three-dimensional, time-dependent flow fields including the laminar-to-turbulent transition process for bounded and free shear flows, fully turbulent flows, flow separation/reattachment phenomena, shock/boundary-layer interactions, and mixing flows.
  - ➔ Advanced 3-D codes generally rely on empirical turbulence modeling and are not always reliable resulting in performance inaccuracies.
  - ➔ Flight scaling for all speed regimes including very low and high Reynolds number flows, vortex management, high lift, scramjet combustion, etc.
  - ➔ Understanding/Modeling/Prediction/Integration of propulsion systems to airframes.
  - ➔ Sonic-boom control/alleviation.
  - ➔ Virtual aerodynamics and flight control, e.g., virtual flaps, porosity effects, circulation control, flow vectoring, etc.
  - ➔ High lift systems
    - ▶ Predict steady state or unsteady flow separation (leading to a inability to reliability predict aircraft lift or drag)
    - ▶ Predict Boundary layer Reattachment and/or re-laminarization
  - ➔ Impact of passive/adaptive/ active flow control, structural control, and noise control technologies for revolutionary vehicle designs
  - ➔ Predict/model/measure thermal radiating flow fields for atmospheric ascent and entry.
  - ➔ Basic understanding/prediction/modeling of extraterrestrial atmospheres to determine a vehicle’s ability to travel within them.

- **The limitations listed above are often related to a lack of knowledge of detailed physics associated with**
  - Scaling effects associated with size, speed, temperature, density, etc., (e.g. Reynolds number, Mach number, Nusselt number, etc.)
  - Flow Separation
    - Induced flow separation (i.e., merging of shock-induced and trailing- edge separated flows, vortex bursting, etc.)
  - Unsteady flows
    - ▶ Control concepts that address unsteady shocks, free-shear fluctuations, circulation, and separation.
    - ▶ Predict/model/design general “unsteady” aerodynamics for rotors, propellers, engines, active flow devices
    - ▶ Predict Buffet onset/post buffet characteristics.
    - ▶ High-speed, high-dynamic-pressure separation phenomena of non-axisymmetric bodies for multistage access to space, store separation, maglev launchers, and autopackage delivery.
    - ▶ Exploitation of inherently unsteady flow fields, requiring knowledge of advanced flow physics, flexible structures and unsteady flight control.
  - Aeroacoustic fields
    - ▶ Acoustical analytic and computational tools, such as sonic fatigue loads (especially for flexible structures), flow/structure interaction, a robust noise/structural interaction model, physics-based jet/combustion/airframe noise prediction technique, interior noise modeling and mid-range frequencies, a robust long-range sound propagation model, and a combined human/machine acoustic detector.
    - ▶ Studying psychoacoustics to determine the annoyance metrics of aircraft noise.
  - Understanding/Measuring/Modeling/Prediction/Application of real gas flow physics associated with all flow regimes, including continuum flow, non-continuum flow, and slip flow
  - Combusting Flows
    - ▶ Understanding/Modeling/Prediction/Application of chemically reacting gas flows.
- **Some of the limitations listed above are also related to the available experimental and computational tools such as**
  - Visualization/immersive simulation to be able to handle/assimilate large quantities of data, both computational and experimental.

- Exploit multiprocessor supercomputer architecture development based on the latest PC chips for maintaining/improving computing capacity necessary for doing research better.
- Experimental techniques that capture complex 3-D time dependent off body flows are too slow, expensive, difficult to use, integrate into available wind tunnel facilities.
- Mach number limit for scramjet performance and operability.
  - ▶ Hypersonic ground test facilities capabilities with the correct gas chemistry, true temperature, and pressure is limited to Mach 6 to 8.
- Investing adequate time to perform literature searches to maintain knowledge of current research within disciplines, travel for face to face meetings, etc. The present workload of most researchers precludes sufficient time for these.

One's own imagination and physics limit the fundamental ideas of "advanced" and "revolutionary" aerospace concepts. Sources of this imagination can be jumpstarted by staying abreast of the state of the art, interacting with those of similar mind, and even reading science fiction. The ability to start with a multitude of ideas and filter them into a few concepts that will revolutionize the transportation industry is too often plagued with costs, timing, and a lack of committed support or dedication. The complexity of flight has a colorful history of ups and downs. This paper will focus on concepts that will lead to revolutionary vehicles. Many of these concepts will springboard from efforts that have previously failed and are being re-visited with new technology enablers. Some of the suggested concepts are radical applications of aeronautics that will satisfy economic and societal drivers.

The paper is broken into sections that will cover aeronautics, space exploration, and non-aerospace applications. Both military and commercial applications will be discussed where appropriate. The required technology development section is intended to highlight areas of research and development necessary to achieve timely and revolutionary advanced concepts.

## **BACKGROUND**

In the fall of 1999, the Aerodynamics, Aerothermodynamics, and Acoustics Competency (AAAC) formed four teams to develop white papers. The four teams were to address, respectively, Advanced Aerospace Concepts, Flow and Noise Control<sup>1</sup>, Advanced Design Tools<sup>2</sup>, and Hypersonic Airbreathing Propulsion Flowpath<sup>3</sup>. The stated purpose of the teams was to:

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It was further stated that performance enhancement, noise and emissions reduction, multidisciplinary integration, and certification by analysis were important considerations. The focus was determined to be the next ten years starting with the current state of the art. This paper documents the efforts of the Advanced Aerospace Concepts team to meet those requirements.

Rather than catalog everything that has ever been done, the team decided to develop a zeit geist, a feeling for the spirit of the times, that was based on existing competency research and on previous and concurrent efforts to develop similar research goals<sup>4,5,6</sup>. To forecast a specific vehicle description far into the future requires the ability to understand the technology development strategy AND the requirements placed on the system by the society that will use that technology<sup>7,8,9,10,11</sup>. This paper will not focus on specific vehicles but will examine technological drivers and the pressures or trends that might influence these technological developments in a future society.

## **Technological drivers**

Technological drivers are technical developments in all fields that act as enablers, providing new means to do things that have either been impossible or prohibitively difficult in the past. Primary technical drivers are those that are particularly applicable to flight and have experienced or can be expected to experience significant advancements. In addition to advances in specific individual areas there is the synergy that can be expected when advances in different areas can be combined in novel ways. Where atmospheric flight and space flight are concerned, high-density energy storage and vehicle weight are critical. Advances in fuel cell efficiencies may well provide sufficient energy densities for commercial flight allowing for electric powered engines. Composite materials have been in development for many years and have not as yet delivered levels of reliable strength to weight performance that had been hoped. There has been considerable progress, though, and there is reason to expect that such progress may accelerate. Electron beam curing may enable use of asymmetric laminates without the residual thermal stresses caused by

high temperature autoclave curing, thereby saving considerable weight and making aeroelastic structures more feasible. So-called nanotubes may provide yet another order of magnitude increase in strength and stiffness over conventional fibers<sup>12</sup>.

Advances in miniaturizing electronic components have already gone to nearly miraculous lengths and further progress is expected. With miniaturization have come speed and increased storage capacity to the point that it is likely a well designed and programmed flight computer can be expected to outperform any human pilot. Airplane design could then be expanded beyond the limitations imposed by human reflexes and endurance. Sufficient reduction in the size of components leads to a synergy with revolutionary consequences: sensors, processors, and actuators embedded in materials can yield 'smart' materials that have the potential of exhibiting characteristics unlike anything seen before. Materials, structures, and even entire systems could behave organically while possessing strength, stiffness, and tolerance for environmental conditions beyond any organic material.

### **Societal drivers**

Societal drivers are social developments that are indicative of changes in the way people view the world and the relative importance they place on the various costs and benefits of daily life. The most significant societal driver appears to be safety. People don't want to die, or even get a scraped elbow. No technical advance will be permitted that reduces safety. Corresponding to safety is reliability, in that safety depends on reliability of flight systems, but also in the sense of the reliability of schedules. Other drivers are desires for physical comfort, quiet (no perceived noise), and low cost. Reducing environmental degradation is far more controversial, but is still very clearly an important societal driver. Due to the rapid advances in technology in nearly all aspects of modern life an emerging societal driver is the desire for what might be termed ubiquitous magical technology: instant gratification of purely personal desires to communicate and to know. While this is primarily related to the electronics revolution, it will inevitably spill over into every phase of life.

### **Constraints**

Constraints can be thought of as brakes rather than drivers. There are a number of significant constraints to the development and implementation of new technologies. One is the belief that infrastructure is limiting. It is assumed that any new vehicle must fit within the existing set of airports, facilities, and traffic control systems. The world has an enormous amount of capital invested in the existing infrastructure, but it should be remembered that none of it existed just a few years ago. Airplanes don't take off and land on rails because the pioneers of flight didn't try to fit within the existing infrastructure. Another constraint is governmental. Governments are conservative and they make rules

that are based on what is, not on what might be. Rules-based constraints can be overcome as long as they are recognized and dealt with as research progresses. There are also constraints based on public perception. No manufacturer will build a truly different airplane because the public reaction to such a thing is to imagine the headlines associated with its first crash. This is a very serious problem and can only be handled by making safety essentially fool proof. While there are technical constraints, real technical constraints are based on the physics of the natural world and we are far from these limits in most areas. The greatest technical constraints are limited imagination and lack of knowledge. If we can just imagine something new, we can pursue the knowledge that will enable its realization.

## **Vision**

So, what might this future world look like? Despite advances in communications, air travel will continue. Airplanes will be comfortable and easy to fly, have inexpensive tickets, easy to maintain, use little fuel, be so quiet as to startle by their unheralded appearance, affect the environment little more than a bird, allow passengers to communicate seamlessly with the outside world, and they will not crash. They will be immensely large, very small, and every size in between and they will not crash. Some will be fast, but they will not crash. Pilots will not fly them, instead they will either command them or negotiate with them, but crashing will not be one of the options. Oh, yes, they will also look very funny compared to what you see today.

Space travel will be fairly common though the numbers will still be small compared with air travel. People and materials will leave the earth's atmosphere and return. Travel to other planets will occur, and exploration of the planets will acquire a new urgency in the search for new resources. For those planets with an atmosphere, a large part of the exploration will be done with atmospheric based vehicles.

Until the need to fight each other can be eliminated, military use of air and space will expand. The imperative to capture the high ground will not change, except that the ground is no longer the limit and for that matter, the sky is no longer the limit! Military aerospace vehicle performance will far exceed the ability of a human to go along for the ride. This will reduce or eliminate the pilot from the on board cockpit.

## **NASA LaRC & AAAC Roles**

Having envisioned a possible future, there remains the question of our role in developing it. The NASA Strategic Plan is delineated in the 1998 NASA Policy Directive (NPD)-1000.1. **NASA is an investment in America's future. As explorers, pioneers, and innovators, we boldly expand frontiers in air and space to inspire and serve America and to benefit the quality of life on Earth.** In the coming years, NASA will implement programs to

achieve a three-part mission encompassing Scientific Research, Space Exploration, and Technology Development and Transfer. NASA's overall program, as outlined in the agency's Strategic Plan, is composed of four Strategic Enterprises, Aerospace Technology, Earth Science, Human Exploration and Development of Space, and Space Science.

The Langley contribution to the NASA Vision is to **be the world leader in pioneering science and innovative technology to enable U.S. aeronautical and space preeminence**. The Langley Mission statement is: In alliance with industry, other agencies and academia, we develop airframe and synergistic space frame systems technologies to enable preeminence of the U.S. civil and military aeronautics and space industries. In alliance with the global research community, we pioneer the scientific understanding of the Earth's atmosphere to preserve the environment.

The role of the AAAC is to develop useable research and technology results that enable program offices to meet program objectives and that enable the Agency to develop future aerodynamic, aerothermodynamic, acoustic, and hypersonic airbreathing propulsion systems and wind tunnel testing technologies. AAAC objectives are to provide relevant technologies and quality technical information, meet planning and execution commitments to program offices, provide and sustain AAAC areas of expertise to meet Agency requirements, and reduce cycle-time and/or cost of conducting experiments without compromising safety.

## **Regulatory Influence**

The role of regulations in the development of aerospace vehicles must not be ignored. The FAA Strategic Plan sets targets for improving safety, security, and system efficiency. The mission of the U.S. Environmental Protection Agency is to protect human health and to safeguard the natural environment — air, water, and land — upon which life depends. These government organizations directly affect planning by NASA LaRC, and the AAAC because of their regulatory nature. Airplanes must be safer and quieter if FAA regulations require it; airplanes must reduce emissions if EPA regulations require it. The lack of motivation of the airframe and/or engine companies and their stockholders to implement revolutionary technologies can often be attributed to the conservative nature of the FAA, EPA, and other regulatory agencies. The influences of these regulatory agencies on the business of designing, building, and flying aircraft and spacecraft must be considered as the planning for the future technology is advanced. It is also important to interact with these agencies so that regulations can be modified with advances in technologies that make air travel safer and certification faster.

## **AERONAUTICS**

In this section the present status and numerous possible advancements of military and commercial aviation are discussed including enabling technologies. A poignant exposition of the actual evolutionary state of aerodynamics, which dispels the widespread myth that aerodynamics is a mature field (where mature suggests that there are no frontiers to conquer) is given. The development and integration of individual components, (e.g. cruise, high-lift, propulsion, structure, noise, controls, etc.) are far from being optimized or mature. Both fixed-wing and rotary-wing aircraft are considered.

### **Aeronautics Paradigm**

A major transformation has occurred in the landscape of the commercial aircraft sales market in the last decade. Previously, the United States (U.S.) dominated the world sales market for commercial and military aircraft, with large airframe companies such as Boeing, McDonnell Douglas, and Lockheed competing for the lion's share of those markets. The emergence of the Airbus consortium made the Europeans very competitive in commercial airline products. To remain viable throughout the 1990's the larger companies consumed many of the smaller airframe companies. The consolidation of several large companies also occurred. Even with consolidation, these companies are currently only dominating the U.S. marketplace. The eroding U.S. market share therefore requires a new direction based on innovative and creative technological advancements for transport aircraft if these trends are to be reversed.

Although there is much resistance from the airframe manufacturers to revolutionary changes in the conceptual design of commercial transport aircraft, there clearly needs to be an effort to consider alternatives. In so doing, there is the possibility to achieve a revolutionary change in design that is clearly superior to the present design.

### **Technology Drivers**

In deciding how to exit the perceived dead end into which aviation has evolved, it is important to look to societal drivers for direction. Technological drivers should only be used to determine the size of the first step. The relative priority to place on conflicting societal drivers then becomes a matter of some importance, but the marketplace is the proper venue for those decisions. The role of the AAAC is to decide how it is best suited to develop technologies; "based on societal drivers" that can be delivered to the marketplace for resolution.



## **Societal Drivers**

Several recurring themes that influence many of the societal drivers have been identified as key areas that NASA will address: **Safety, Noise, Efficiency, and Environment**. It is not unusual for these drivers to be in conflict with one another. It is also recognized that military and commercial requirements place different demands on these key areas. The following sections will highlight each of the areas and identify several advanced concepts for military and commercial applications.

## **SUBSONIC MILITARY AVIATION**

Many of the advances in commercial aviation have been brought about through military applications (see appendix). The military's need for performance and supremacy continues to push the aerodynamic envelope and technologies that support it. Survivability on the battlefield may soon drive aircraft to be pilotless, generating a new class of aircraft with new requirements. The Defense Advanced Research Projects Agency (DARPA) is virtually synonymous with advanced concepts military research. NASA's work should be complimentary to DARPA, DOD, and other government programs.

While advances in military aviation may be pushing toward unmanned aircraft, the enabling technologies that will be necessary for these vehicles could also have applications to civil aviation. NASA is in a unique position to bring appropriate military technologies to civil applications.

## **Military Aviation Enabling Technologies**

### **Flow Control**

Managing the flow fields around complex aircraft components has been examined for decades (aerodynamic control surfaces, vortex generators, fences, etc.). It is recent advances in materials, miniaturization, and improved speed in electronics that have opened the door to new and innovative ways of controlling macro and micro-scale flow characteristics. A broad range of active and passive flow control techniques can be used to manage flow that will affect performance, noise, safety, etc. Applications may include Adaptive Performance Optimization ("virtual shaping of an aerodynamic surface to ensure that the aircraft is always flying the optimal configuration for a particular flight regime); control of all types of flows (laminar, turbulent, vortex, combustions, mixing, or separated); anti-noise; favorable wave interference; and thrust vectoring. With these flow control techniques, significant improvements in aircraft performance may be possible, from the largest transports to the smallest uninhabited air vehicles. Aircraft structure could be freed from flight control functions, dramatically reducing weight. Flight control could be possible

where there currently is none (munitions). Aircraft configurations could be enabled that were previously prohibitive.

At optimum, flow control systems will be closed-loop. That is, sensing the flow, comparing that flow to a model of the desired condition, calculating what actuation authority is necessary, and implementing it. The requirements for and understanding of this enabling technology is still in the embryonic stages. Critical to the success of implementation of these technologies will be the understanding of unsteady flow physics these micro devices exert on the global flow. This includes the scaling of the steady and unsteady spatial and temporal flows that are being controlled; flow sensors; closed-loop controls; CFD modeling for prediction and design of turbulent/unsteady flows; and the devices themselves (design, bandwidth, durability, susceptibility to environmental effects (rain, bugs, etc.), control power, etc.).

While these tools are being developed, much can be learned by intelligent application and exploitation of these devices even before the details are fully understood. Experimental work should not be put aside until the CFD codes are robust. For nearer-term payoff, flow control can be applied in a more localized fashion either in conjunction with conventional controls or with shape-control. The reader is referred to a separate White Paper dealing exclusively with flow and noise control, where the details of required research are presented.

## **Shape Control**

As early as the Wright Brothers, flight control was implemented through macro-scale shape control, or wing warping. Put in more modern terms, heavy, complex flight control systems (flaps, ailerons, spoilers, elevators, and rudders) can be eliminated through the use of bendable skins with "smart" underlying structure. Sometimes called "continuous moldline" or "morphing," this technology also has the benefit of eliminating flap edges, which are a source of noise and increased radar signature. Although the technology is largely unproven, it is believed that some combination of shape and flow control will be necessary for applications where shape control alone would cause flow separation (e.g., high-lift systems) which would reduce the effectiveness of the system. If shape-control systems can react fast enough, the total structural weight of the aircraft can be reduced through active aeroelastic control. Currently the structures and materials disciplines include control effector research in this area, but are often unaware of the details of the aerodynamic applications, and the attendant requirements, so much more multidisciplinary work is needed. And when a structures practitioner asks an aerodynamicist what a continuous flap shape should be, there is often no answer because so many years have been devoted to optimizing flap gaps and overhangs. Some basic "what if" work needs to

be accomplished to understand what shapes are desirable from a lift/drag/control standpoint.

On a smaller scale, micro-vortex generators and passive porosity can be considered shape control if they are selectively deployable. The explosion in the availability of micro-machining techniques and in micro-electrical mechanical systems (MEMS) devices are bringing such applications closer to fruition. Although it will be discussed more in the "Uninhabited/Micro Vehicles" section, understanding low Reynolds number flows and having the computational tools to predict the behavior and design of such systems is critical for the widespread acceptance of micro flow/shape control devices.

### **Cloaking**

High performance and reduction of observables, whether visual (contrails), acoustic, or at frequencies beyond the visual and audible range, is usually of paramount importance to military missions because they directly affect the survivability of the aircraft and the pilot. While these considerations may at first seem to have only military applications, they actually offer many possible civil aviation benefits. If flap edge noise can be eliminated through continuous moldlines or if jet noise can be directed away from the "threat" area for military vehicles, then noise can be similarly reduced/directed away from near-airport communities. Similarly, minimum length convoluted diffusers are being designed into the Blended Wing-Body (BWB) aircraft and other innovative engine applications.

Preventing contrails for military and civil applications is important. Current thought suggests that contrails are a bigger contribution to atmospheric pollution than  $\text{NO}_x$  or  $\text{CO}_2$ . Research into an environmentally friendly means of discharging or eliminating contrails has direct applications to both the military and civil aviation fleets.

### **Aeropropulsive control**

Although much more "near-term" than the previously discussed technologies, it is recognized that aeropropulsive control (also known as "thrust vectoring") has already been flight-demonstrated on the XF-22, X-31 and SU-37. Thrust vectoring is of particular interest to the applications of uninhabited or micro vehicles. This is to save the weight and complexity of a separate flight control system. Although adequate flight control, even in engine-out conditions, is essential for man-rated aircraft, the same may not always be true for uninhabited air vehicles where risk, loss, or recovery issues are different. For example, an unmanned aircraft could utilize a parachute system for engine-out conditions, with recovery at a later time, or self-destruct to prevent capture of the technology.

Conventional flight controls in high-performance fighters are already capable of generating more "g" forces than a pilot can endure. Uninhabited vehicles with more complex control systems could be much more maneuverable than manned fighters over the

whole range of flight conditions. Although much research was accomplished<sup>13</sup> in the field of thrust vectoring in the 1970s - 1990s, lighter, less mechanically complex thrust vectoring systems will be required for small uninhabited vehicles, and would have a payoff for larger vehicles as well.

### **Military Micro vehicles**

Aerodynamics at very low Reynolds Number is currently not well understood, and can be very different from aerodynamics at the typical "millions" Reynolds number scale. Understanding of the flow physics at these scales, computational tools to predict their behavior, and finally, design tools for such vehicles must be developed. Multidisciplinary optimization of these vehicles is critical when every gram of weight counts. Further integration of propulsion and control systems and acoustic considerations must be addressed from the outset. MEMS may also play an important role in the control of micro vehicles. At these physical sizes, unsteady (periodic) aerodynamics ("flapping-wing" technology) may also be a design option.

### **Military Rotorcraft**

A military capability for vertical takeoff and landing (VTOL) at unprepared sites will be needed as long as ground troop insertion, supply, and evacuation into a battlezone is required and there are enemy ground troops to eliminate. Rotorcraft fills a unique niche in that they achieve VTOL without significant harm to the landing surface, unlike jet VTOL. Advanced configurations which have more heavy-lift capability (quad-tilt rotor, for example) and are more survivable ("stealthy") will be needed for the foreseeable future.

## **SUBSONIC COMMERCIAL AVIATION**

Historically, commercial aviation has benefited from the high-risk research conducted on military aircraft. However, the advances in military applications can only go so far, as civil aviation faces many more regulatory restrictions. These restrictions force differences in military and civil aviation in the areas of environmental noise, environmental emissions, and safety.

### **Civil Aviation Enabling Technologies**

There are many similarities in the enabling technologies for both military and civil aviation. The definition of what is revolutionary and what is not will be different for military and commercial aviation. However, flow control, shape control, and aeropropulsive control are enabling technologies that are common to both. Safety and the tolerance of the community often govern the differences in the thrust for developing the required enabling

technologies for military and/or civilian flight where aircraft fly. This is emphasized in the environmental noise and environmental emissions issues described below.

## **Environmental Noise**

One area in which societal desires most clearly argue for a revolution in aircraft configuration is that of noise. New and future regulations will reduce the noise impact on the community surrounding airports. Past programs have made substantial progress in reducing aircraft noise within the framework of the current airframe designs. There is room for some further progress within the same framework, but the increasing popularity of flight may well render such progress moot. Thus, noise reduction must be considered a primary technology area that requires attention.

Aircraft noise can be divided into two categories: interior and exterior. Interior noise affects the people in the airplane and exterior noise affects everything else. Efforts to control interior noise can presumably be applied to any aircraft configuration. While some airplane configurations may be easier to manage than others, it is difficult to see how reduction of interior noise requires fundamental new configurations. Reduction of exterior noise, on the other hand, favors certain concepts and configurations over others. Exterior airplane noise is an issue involving source noise level, frequency content, proximity, and directivity. Efforts to date have focused on source noise level. Substantial further progress will require shifting attention to the other issues.

Sound is reduced by distance, and higher frequencies are reduced more than lower frequencies because of differential atmospheric absorption. Keeping airplanes away from people is then one useful way of reducing noise. This is already done with many aircraft taking-off at steep angle of attacks then throttling back the engines once the aircraft has reached a safe altitude. These procedures are necessary to meet existing noise restrictions around the world. More could be done in this area, but with fewer expectations on current airplanes. Assisted take-off like those used on aircraft carriers could be done with silent runway based systems using electric motors. The airplane engines would not be required to run at a high power setting until the airplane was farther away. This would have the further benefit of reducing wear on the engines. Approach to landing is now done along a 3° glide-slope that keeps the airplane close to the ground over great distances. A much steeper angle would keep the airplane farther away from people. Deeply throttling back the engines during landing would reduce the noise even more. Safety drives the existing glide slope requirement as well as the need to keep the engines running at a relatively high level. The Space Shuttle currently makes fairly steep unpowered landings; so it is evident that such a thing is possible. The safety benefits of this type of approach could be tremendous. An airplane designed to make unpowered landings, especially slow landings, would not be

in any more jeopardy of crashing due to engine failure than crashing a conventional airplane at a 3° glide-slope.

Since the atmosphere better absorbs higher frequencies than lower ones, sound sources on airplanes should be designed to generate less low frequency noise even at the expense of additional high frequency noise. Human response to sound is a complex field of study, but certain simple concepts can be used. One is that pure tones are bad. They stand out, they are noticeable, and they are identifiable and distinguishable from other sounds. A mosquito makes very little noise, but its very identifiable whine gets your attention. The broadband noise of an airplane, on the other hand, is little different qualitatively from the broadband noise of other sources.

The directivity of airplane noise is an area that has seen little attention and yet shows some promise. The only exterior airplane noise that matters to people is the noise that reaches them. If an airplane makes more noise but that noise is directed away from people, they won't be bothered by it. Tailoring noise sources to have directivity patterns where noise is directed upward will further reduce the annoyance caused by airplanes. And yet, addressing noise sources (such as engines or flaps) as individual items that are in some sense independent of the airplane is part of the paradigm that needs to be abandoned. Tailoring engine noise directivity is one solution to reducing noise on the ground. A better solution is to place the engine above the airplane where the airplane structure shields the ground (and the people there) from the noise. The very idea of designing an airplane with low noise as an important design parameter established at the beginning of the design cycle is a paradigm shift of the first magnitude.

The Blended Wing Body airplane is an example of this paradigm shift, but it doesn't go far enough. Using large engines with very high bypass ratio fans to reduce jet noise is one way to reduce source noise levels. But moving the engines forward allows shielding of aft noise as well as forward noise. Noise can be further directed upward by “scarfing” the inlet and exhaust nozzles. If this is not an ideal cruise configuration, the engines can be designed to be moved during flight from take-off positions to cruise positions (and then to landing positions, if necessary) where each engine position and orientation is accompanied by a unique nozzle configuration.

Another way to reduce noise is to use many small engines instead of a few big ones. Small engines could be designed to have greater high-frequency noise content that would be absorbed by the atmosphere. Very small engines could be distributed and/or embedded in the wings with inlet and exhaust both being positioned atop the wing. Designing an airplane with many small engines has favorable safety implications. Loss of an engine is less important for an aircraft with thirty engines than it is for an aircraft with one or two.

Even unpowered flight generates noise as air flows over the structure. If propulsion noise is reduced or shielded, flow noise becomes a more obvious issue. At the low speeds

of take-off and landing, a large part of the problem is the noise from turbulent flow interaction. The very high-lift devices that make possible the slow approach to landing are responsible for this noise. Generating additional lift to make possible a slower and much steeper approach to landing would seem to be a self-defeating proposition. Understanding the sources of airframe noise, though, makes it possible to reduce that noise for conventional wing and landing gear design. Fairings could be used on landing gear and relatively simple changes to slat and flap design could reduce their noise. More advanced circulation control over wings, fuselage, or their blended structure would generate high lift with less noise on more modern designs. This control could be from Coanda surface blowing, compressor bleed blowing, micro-machined low-power synthetic jets, or fluidic actuators. Active smart structures, vortex generators, and variable wingspan along with riblets and fringed trailing edges would begin to make an airplane approach bird-like efficiencies.

With noise generation dependent on the fine details of flow fields, the only way to significantly reduce noise while maintaining safe, efficient vehicles is to more fully understand the flow over moving structures. Understanding and manipulating turbulent and unsteady flow are vital. There is a need for an advanced unsteady turbomachinery aerodynamics CFD codes and a high order duct acoustics propagation codes. On a larger scale there is a need to develop a propulsion/airframe aeroacoustics (PAA) code that can use CFD results that describe the 3-D flow field over an entire propulsion/airframe structure. These codes would be used to determine the effect of the local flow field on propulsion noise generation as well as the effects of shielding, diffraction, and reflection on the propagation of that noise. With a better understanding of the flow field into engines, the proper blend of passive treatment, adaptive liners, and active noise control can be ascertained. The use of these codes in trade studies is at least as important as their use for physical understanding. Designing for environmental effects is far more effective than dealing with inadequacies later.

## **Environmental Emissions**

Another area where societal drivers argue for a revolution in aircraft configuration or operation is that of chemical emissions. As with noise, chemical emissions are an area of concern not only for those who fly, but even (or especially) for those that do not. Concern for emissions has traditionally focused on carbon dioxide, oxides of nitrogen, and particulate. Only more recently has the issue of water vapor emissions been raised. It has been suggested that global warming has been caused as much by anthropogenic cirrus clouds (derived from aircraft contrails) as by excess carbon dioxide. Thin, high-altitude cirrus clouds have been shown to have a net warming effect on the earth as opposed to the net cooling effect of thick clouds. Simply changing to hydrogen fuel would not reduce water

vapor emissions though it might reduce production of ice crystal nucleation sites. Changing to a closed-cycle propulsion system, adding precipitation-enhancing dopants to the fuel, or flying where cirrus clouds don't form are potential solutions. This is an area where clearly more research is truly needed.

Emission reduction can be achieved in at least three ways:

- new technology incrementally applied to conventional designs to gradually reduce chemical emissions, **evolutionarily**,
- apply existing technology in new ways to allow the removal of systems from an aircraft, i.e., lose weight and/or change operational characteristics, **revolutionary or evolutionarily**,
- devise radically new technologies and concepts that completely eliminate chemical emissions, **revolutionarily**.

Evolutionary emission reduction methods include all of the usual incremental technological “innovations”. Examples include direct fuel efficiency improvements (via advanced engine materials and components or flow path improvements), weight reduction (primarily via new materials systems or structural advances; secondarily via vehicle resizing due to fuel efficiency gains or drag reductions), and lift-to-drag ratio improvements (e.g., increased aspect ratio, airfoil tweaking, or drag clean-up).

Revolutionary emission reduction can rely upon extensive changes to the airframe, onboard systems, and aircraft operations to minimize weight and engine-on time. Methods could include innovations such as maglev catapults to reduce or eliminate takeoff emissions and/or eliminate landing gear, high-bandwidth communications to enable ground-based digital flight control systems and minimize onboard avionics, thrust vectoring to eliminate tails, designer aerodynamics (e.g., circulation control, passive porosity, synthetic jets, etc.) to enable virtual control surfaces, and synthetic vision to eliminate flight crew and passenger windows.

Both the evolutionary and many revolutionary approaches to emission reduction have a major drawback: emissions are not completely eliminated. Based on recent analysis, even if a true zero-emissions aircraft were introduced into the fleet within the next 10-15 years, the CO<sub>2</sub> overall emissions from the civil fleet will not return to 1990 levels (per the Kyoto Agreement) until about 2050. If a new type of aircraft that reduced CO<sub>2</sub> emissions by 80% were introduced around 2020, emissions would finally level off around 2050 at 1990 levels plus 67%. True zero-emission aircraft (at least in terms of one suitable for revenue service) are far beyond the current state-of-the-art. Propulsion is the major hurdle. Fuel cells of various types could hold promise, but aircraft that are powered by fuel cells gain weight as they operate (vs. losing weight in the current paradigm). The fuel cell by-products (e.g., water) could be jettisoned in-flight to lose the weight, as long as the by-products do not persist in the atmosphere. Liquid hydrogen (LH<sub>2</sub>) has similar issues. If LH<sub>2</sub>



is used as fuel (like Jet-A today), the only resulting emission is water vapor. Beaming power from the ground or from space to the aircraft does not currently look feasible due to atmospheric effects on the beam.

### **Short Take Off and Landing and Vertical Take Off and Landing Aircraft**

Helicopters satisfy a number of transportation, commercial, and emergency and needs due to their vertical take-off/landing and hovering capability. In general, helicopters travel at a forward speed of around 200-mph, have flight duration of two to three hours, and have a range of about 600 miles. They have higher fuel consumption than fixed-wing aircraft for travel over a given distance. Some improvements have been made in forward speed by introducing jet or propeller systems in compound helicopters. Advancements in materials have made helicopters lighter, stronger, and safer. A major problem with helicopters continues to be the vibration and noise levels they produce. Tilt-rotor and tilt-wing aircraft are hybrids in that they have the vertical take-off/landing and hovering abilities of helicopters but have the high-speed horizontal flight abilities of airplanes. They will travel roughly twice as fast and twice as far as conventional helicopters. As with helicopters, vibration and noise are major issues.

Vertical take-off and landing (VTOL) and short take-off and landing (STOL) aircraft pose a somewhat more difficult aerodynamics challenge than conventional aircraft. Advanced transport airplanes that land slowly and steeply won't significantly reduce the need for those that hover and land vertically. Using structure to shield noise has significant penalties when thrust is directed downward, so other solutions must be found. Shrouding rotors, at least small ones such as those found on tilt-rotors, may provide a solution. Another approach is to provide adaptive blades that change length or active blades made of smart materials that change twist distribution to alleviate noise while maintaining performance. Regardless of which approaches are used to enhance efficiency or reduce noise and vibration, an understanding of unsteady flow is vital. These aircraft experience periodic and random unsteady flow over airfoils under steady state, unsteady flow during transition between flight regimes, and complex unsteady flow/structure interactions during take-off, hover, and landing.

### **PERSONAL or GENERAL AVIATION:**

Commercial and business aviation benefits the most from substantially new vehicle configurations, but general aviation (or personal aviation) also has room for improvement. If the AGATE and SATS programs yield only a fraction of the increase in flying that is projected, noise will become a significant issue. Most of the small airfields from which such vehicles would fly are located in areas where people are used to lower noise levels. Cost considerations generally lead to intermittent-combustion powered, propeller driven vehicles

that work best in a tractor configuration, but small turbine engines have tremendous advantages if cost can be reduced. Many-bladed, lightly loaded, highly-swept, very thin propellers can be used to reduce noise, but only if coupled with a narrow, symmetric cowling that reduces unsteady loading on the propeller. Concurrent design of airframe and propeller with low noise as a primary consideration is necessary. High technology must continue to flow into even the less expensive aircraft.

Current efforts, including AGATE, in General Aviation technology have focused primarily vehicle technology. Langley has initiated the SATS program to examine an integrated new civil air transportation network. The SATS program is looking at using GPS and computer networks to direct flight traffic. It is also evaluating a synthetic vision system to improve small aircraft visibility in inclement weather, and it is examining the coordination of ground transportation. However it is not looking at the aerodynamic aspects of the technology.

Research in low Reynolds flight and also in unsteady aerodynamics in low speed flight would be of particular value to personal aviation aircraft. Combining a better understanding of the aerodynamics with improved understanding of active stability and control capabilities could be used to improve the safety and performance of lightweight aircraft flying at low speeds and increase the smoothness of take-off and landing. This in turn could make for a vehicle much easier to fly and thus attract a larger pool of pilots to operate the aircraft.

Ad-hoc experimental aviation designs, made by both professionals and enthusiastic amateurs have led the development of improved personal aircraft. There is certainly a need for NASA aerodynamic researchers to also participate in this field. As the number of personal aircraft increases, the problems of safety, comfort, noise, fuel efficiency, and speed will become as important just as in commercial aviation.

### **Flying Car:**

The rationale of using a personal flying car is to bypass the limitations imposed by the road system (avoid heavy traffic, and travel where no good roads are available), and also travel about as fast as aircraft, but point to point rather than multimode travel (car to plane to car). The current state of technology is in a very early phase. Several concepts, which include the Aerocar CRX, the Roadrunner, and the Lincair, have been conceptually designed but are at an early stage of testing and refinement.

Several advances in technology or infrastructure are needed to improve this design concept. First the use of different materials to reduce weight and increase durability need to be employed. Materials that would minimize defect propagation and even allow for passive repairs would be ideal for this technology.

The flying car would also benefit from the increase in information technology to make air travel safer. Current UAV systems such as GlobalHawk, Darkstar, and Predator have demonstrated automated guidance and control of aircraft. Derivatives of such systems could simplify the task of flying allowing greater accessibility to the air. The flying car would definitely benefit from studies on unsteady aerodynamics. Small cars can typically be blown 1-2 ft on a highway traveling at moderate speeds due to cross wind gusts. Studies to characterize unsteady cross-flow aerodynamics could aid in the development of an active flow-correction-control system. These studies would also aid in the take-off and landing portions of the air-car flight as well.

### **Commercial Micro-Air Vehicles:**

Micro-Air Vehicles with cameras and on-board instruments can conduct police surveillance, search for lost persons, assess damage from storm or earthquake, sample the atmosphere, and do numerous other earth-based uses. In addition, they may be useful as wide-ranging explorers on other planets. These types of vehicles need to be small, have reasonable speed and endurance, and be reliable.

The current leading Micro-Air Vehicle is the “Black Widow”, made by Aerovironment. This vehicle can fly at 43 mph for 22 minutes. Many of the present vehicle designs suffer from frequent crashes due to their small size/mass and low speed. A paper by Dudley showed that there is a distinct breaking point in the aerodynamics employed by flying machines both biological and mechanized which occurs around the six-inch wing span. The aerodynamics of flight for vehicles under a six-inch wing span is still not clearly understood. An understanding of the aerodynamic forces at play in this low Reynolds number regime should be examined to extend the size to as small a vehicle as practical.

Studies of low Reynolds number flight, flapping wing flight, hovering, and unsteady aerodynamics are needed to begin to properly understand this class of vehicles. Currently DARPA is searching for a fully controllable Micro-Air Vehicle for military surveillance and hazardous cloud detection. Most research areas are focused on making a workable vehicle with size and range specified. Very little fundamental aerodynamic work is being performed on this class of vehicles.

## **HIGH SPEED CONCEPTS**

### **Supersonic**

Commercial supersonic flight clearly falls within a separate regime from commercial subsonic flight. While there have been many successful military supersonic aircraft for decades, there have been no economically successful commercial supersonic aircraft. The reason, simply put, is that the economics are different. That is the economics between military and commercial aviation is different, and the economics between subsonic and supersonic flight are different. Even so, with all of the success of supersonic military

aircraft, none of them have been transports. Commercial success in supersonic flight will stem from designing vehicles that will generate sufficient income (by charging a premium over subsonic flight, opening new markets, or by a currently unimagined paradigm shift) to justify the additional expense of their development and operation. The constraints that must be met are those of the long-range subsonic fleet, and then some. The additional constraints are primarily environmental: sonic boom and emissions at a higher altitude. Complicating the issue is that just meeting the constraints faced by the long-range subsonic fleet is more difficult for a supersonic fleet because take-off and landing are low speed, (hopefully) quiet events for which supersonic cruise configurations seem ill suited.

### **Enabling Technologies**

Successful development and demonstration of the key technologies for quiet, efficient supersonic cruise flight will enable valuable and unique vehicles, with a range of military and civil applications important to the U.S. national security and economic competitiveness.

These enabling technologies are well known and exist at varying stages of maturity. Successful supersonic cruise vehicles will require: supersonic flight over land, with minimization or elimination of the sonic boom; low-noise, efficient supersonic inlets, engines and nozzles; high levels of aerodynamic cruise efficiency; high lift systems with safe low speed flight, and advanced lightweight airframe structure. Progress on these technologies was made in the recent U.S. High Speed Research Program. However, these technologies were not fully matured, and more importantly, most of them were not demonstrated in flight.

Methods for shaping supersonic airframes to minimize the sonic boom have been developed and tested at small scale. The key remaining challenge is the validation of these shapes at large scale in the real atmosphere. Moreover, simply shaping the airframe to soften booms may not be sufficient. Other advanced concepts may be needed to achieve a sufficiently low boom level. These technologies must be integrated in a manner that does not detract from overall aerodynamic efficiency. Technology that allows pilots to determine the location and loudness of the sonic boom on the ground may also be required. A near-term test to determine the boom “floor” is highly desirable. If a supersonic lifting shape with a minimum of boom-producing features (e.g., without inlets) creates a sonic boom greater than the acceptable overland level (somewhere near 0.5 psf at the ground), further pursuit of boom-softening technology may be irrelevant.

Attractive technologies for very efficient supersonic cruise aerodynamics include drag reductions obtained through laminar flow<sup>14</sup>. Concepts for achieving this laminar flow naturally via novel wing design and through active flow control have been explored but require significant additional development and flight demonstration.

Technologies for the design of supersonic propulsion systems that are quiet during takeoff and landing operations still require considerable work. The challenge is to deliver suppression of engine noise without severe increases in weight and loss of engine thrust.

Advanced structures and materials technology concepts have been explored for application to the high temperatures experienced in supersonic flight. Analysis shows they provide substantial weight-reduction benefits. Further maturation and understanding of manufacturing techniques is required. Weight has a powerful effect on sonic boom, but boom levels low enough for overland supersonic flight cannot be achieved (on an economically relevant transport) via weight reduction alone.

One may note that some combinations of technologies may be mutually exclusive on supersonic aircraft (e.g., low-boom and supersonic natural laminar flow), at least, as the phenomena are currently understood. This should emphasize even more strongly the need for integrated multidisciplinary research on the technical challenges.

### **Shift in Direction**

The solution to this apparent high-speed dilemma is to abandon concepts for supersonic airplanes that are merely 'pointy' versions of conventional subsonic airplanes. Some of the ideas that are proposed for developing a new subsonic fleet will work for a supersonic fleet, although the implementation will be different. For example, the designer can: use vectored thrust and flow control in place of conventional control surfaces; make vehicles that are reconfigurable for take-off, cruise, and landing; include environmental considerations early in the design process with noise; use propulsion concepts that are not merely scaled up military fighter or bomber engines, but may include different engines for different speed regimes: high bypass turbofan for take-off, turbojet for cruise, nothing for landing; use an integrated structure that is not necessarily a fuselage with wings pasted on and an empennage pinned to the tail of the donkey; and use synthetic vision instead of windows so you can put the aircraft commander (pilot) where weight and balance dictate. More new ideas will be required. Methods to eliminate (or manage) sonic booms head this list. The primary recommendation is to stop assuming that an idea is bad because it was discarded in the past, or is not ideal for subsonic flight. Trade studies should be performed as close to the start of the design process as possible with the highest level of fidelity available.

Needed key technologies could be successfully developed using a carefully planned technology-development program involving conceptual design and analysis, ground tests (wind tunnel, jet noise facilities, CFD, etc.), and flight tests in two stages. First, the key design methods and advanced concepts should be validated to determine the achievable performance levels for boom and noise reduction. Such results are essential to assess the feasibility of future supersonic applications. The second stage of work would explore the

technology integration and validation for specific design applications of interest for both military and civil applications, at sufficient fidelity and scale to allow confident extrapolation of results to full-scale applications.

## **Hypersonic Flight**

The arena of hypersonic flight within the atmosphere is one that has been studied for decades, but has had applications limited to rocket-based flight to orbit (both ascent and entry), as well as the NASA/Air Force X-15 rocket-based aircraft flight test program. Exploitation of this speed regime within the atmosphere for military and commercial benefits is still in the early stages. The primary benefit exploited from this speed regime is flight time. A military vehicle traveling at five to ten times the speed of sound could provide worldwide coverage in about four hours. Increasing speeds to higher than Mach 15 would provide insignificant reductions in block time for either military or civil aircraft—the Earth is simply not large enough to warrant it; therefore, this speed is probably the limit for hypersonic cruise applications. However, speeds to Mach 25 are required for insertion to low Earth orbit.

## **Military Applications**

There are several hypersonic applications that are of interest to the military community. The first of these are missiles and weapons that are highly agile and effective, i.e., smart bullets. Advances in materials and controls technology could make hypersonic rocket-based penetrators an important asset in future conflicts. Furthermore, as the enemy continues to dig deeper into the Earth to avoid aerial attack, penetrator weapons that are highly accurate may play an important role. Another high-speed, small-scale munition application is the DARPA supersonic miniature air-launched interceptor. This would provide cruise missile defense by using a low-cost infrared sensor on a small missile to seek their large rear-aspect infrared signatures and overtake the inbound missiles from behind. As smart aircraft systems, MEMS, and small-scale propulsion systems (~2-inch diameter) continue to show promise in the lower speed regimes, exploitation at the higher speeds is a natural progression to provide new levels of agility. This would be coupled with sensor/feedback miniaturization from the electrical/computer-engineering world to provide autonomously flying vehicles.

The second military application would be hypersonic weapon systems that would exploit the oxygen in the atmosphere for the combustion process (instead of carrying it in tanks or relying on solid propellant). They could be used for global-reach missions while maintaining limited observability and exploiting high speed. These systems would require hypersonic airbreathing engines, a concept that has been researched for almost 50 years, but has seen NO flight demonstration. NASA's Hyper-X program will finally bring the

scramjet engine concept out of the laboratory and test it in the atmosphere. One known truth about hypersonic airbreathing propulsion is the need to formally integrate the propulsion system with the airframe in the design process. Its importance is noted in the fact that hypersonic airbreathing propulsion flowpaths is the subject of a separate white paper in this series. The reader is strongly encouraged to peruse that document for additional information in this area. While the basic concept of a scramjet is not new, the technologies needed to make it a viable propulsion system option are not very mature. As important as the component is to a revolutionary breakthrough, the systems studies needed to increase their flight readiness level is an important avenue of research. Other issues of importance to hypersonic airbreathers include the need for advanced materials, simplifying systems, improving maintainability, and improved reusability by understanding the extent of thermal and acoustic fatigue.

The uses of hypersonic airbreathing vehicles can also be extended to human-tended flight, both for military applications (global reach reconnaissance, delivery, strike) and commercial applications (Trans-Pacific passenger and cargo flights in three hours).

## **Access to Space**

Aforementioned, hypersonic flight is required for access to space. Current launch systems are either not reusable or only partially reusable. The future holds many promising technologies for improving the safety, reliability, and affordability for space access. Among these ideas are single-stage-to-orbit vehicles, that are either rocket-based or rocket/airbreather based, and multi-staged vehicles that use airbreathing propulsion for the lower speeds and rocket propulsion for higher speeds and orbital insertion.

One approach to hypersonic airbreathing space-access vehicles is with an over-under propulsion configuration with turbo-ramjets for the low speed system and scramjets for the mid- and high-speed system. (Currently, the upper limit on scramjet operating speeds is not known and is a worthy research topic on its own.) Obviously, there is an altitude limit for operating scramjets (due to lack of sufficient oxygen) which requires that a rocket-based system is needed for the final acceleration to attain low Earth orbit.

Scramjets are being flight-tested in the Hyper-X program, and complete vehicle configurations are being studied in the Spaceliner 100 Program. These airbreathing propulsion systems require airframe integration in the design of the vehicle. The vehicle forebody serves as a compression surface for the inlet flow into the airbreathing engine, and the afterbody serves as the nozzle expansion region for increased vehicle thrust.

Hence, an accurate understanding of the fluid flow over the complete vehicle is required, including boundary-layer transition, separation zones, and combusting flowfields.

Furthermore, airbreathing-engine concepts are actively being considered as stages in a

multi-staged vehicle; thus, aerodynamics of vehicle separation is a critical enabling technology.

Another propulsion system options for hypersonic airbreathing space-access vehicle are the so-called rocket-based combined-cycle engines that utilize miniature rockets integrated into a dual-mode scramjet flowpath. These miniature rockets can be used to provide thrust at take-off and for orbital insertion. This method allows the rockets to be used when scramjet performance degrades, but is hampered by the need to carry additional oxidizer, reducing its payload fraction. One possible solution to the thermo-acoustic fatigue issues for high-speed scramjets is an engine that utilizes fuel injected upstream of the throat and ignites near the throat due to shock-induced pressure and temperature rise. This concept is known as either a pre-mixed, shock-induced combustion engine or an oblique detonation wave engine. Preliminary studies have shown a difficulty in two areas: (1) getting the fuel to sufficiently mix with the captured air upstream of the inlet, and (2) avoiding premature combustion upstream of the throat. However, if these problems can be overcome, the result would be an engine with reduced weight and heat load, resulting in increase fuel efficiency and thrust.

There are also some technologies related to airframe-propulsion interactions and integration that can be exploited in the hypersonic regime. The first of these is favorable shock wave interference, in which shock waves produced by elements of the geometry judiciously interact with other parts of the geometry to minimize or eliminate the vehicle's wave drag. This concept is a point design, but adaptable structures could make this a multipoint-optimized design. Second, the design capabilities for waverider vehicles have been extended to more complex generating flowfields to improve the captured engine inlet flow. Conical derived waveriders possess a pressure gradient away from the surface, yielding a non-uniform flowfield for the compressed flow entering the inlet. Using an osculating-cone inverse design technique, flowfields are nearly uniform in the area upstream of a representative engine position and good vehicle volumetric efficiency can be achieved. Finally, a concept for utilizing deflection of the gross thrust of a scramjet engine may be able to be used to both decrease the wing size and weight at a given altitude or to increase the cruise altitude of a prescribed configuration. All of these concepts have potential merit, but analytical, computational, or experimental assessment has been very limited.

In terms of reducing the cost of access to space, a significant amount of payload either is or could be made to withstand significantly high g-loads, e.g. fuel and building materials. This would permit the use of a new type of launcher that utilizes sequentially triggered blast waves within an evacuated tube to accelerate a payload-carrying projectile to near orbital velocity in a relatively short distance. Issues that need to be addressed for



such a vehicle include nose-tip survivability at these speeds (near sea level), controllability of the projectile, and structural design to withstand the high g-loads.

In the farther term, another approach to boost payload to orbit would be with electromagnetic radiation, such as microwaves or lasers. This would result in environmentally friendly propulsion systems (e.g., magnetohydrodynamic drives) with little or no exhaust. Currently, proof-of-concept tests have been for low speeds and altitudes. Other approaches to advances in hypersonic propulsion include high energy density fuels and fusion power. The high energy-density fuels are being studied by the Air Force, while an investment of modest size and duration is required to determine the potential feasibility of fusion propulsion and power.

Before leaving the topic of hypersonic vehicles, it is important to note that, aside from pulse facilities, there are no ground test facilities that completely simulate hypersonic flight (both in terms of conditions and gas constituents). Detailed ground testing is needed to validate concepts and preliminary designs prior to flight test development. Efforts should be made to fully understand the requirements of a full-simulation hypersonic ground test facility and work towards eliminating that void.

The emerging field of molecular nanotechnology provides some potential technological applications for hypersonic flight and space access, although they are still highly speculative. Molecular nanotechnology is defined as the thorough three-dimensional structural control of materials, processes and devices at the atomic scale [Globus, et. al., 1998]. For launch vehicles, the construction of material systems by arranging atoms on the surface of diamonds (diamondoid materials) could provide a strength/mass ratio that is over 50 times higher than for titanium, thus reducing the vehicle weight so that it could actually be lighter than the payload. In the nearer term, improved structural materials are being addressed using carbon nanotubes. Furthermore, carbon nanotubes are being studied for use as vehicle thermal protection. The current methods of carbon nanotube production typically create a tangled mat of nanotubes with a very low mass/volume ratio. These tubes should be able to withstand the high temperatures like graphite composites, but being in a tangled mat may prevent or limit ablation.

# **SPACE EXPLORATION**

## **SPACE TRANSPORTATION CONCEPTS**

The major thrust of the NASA's Space Transportation Program is the development of a Reusable Launch Vehicle (RLV) to replace the aging Space Shuttle. The critical requirements of this new vehicle, designated 2<sup>nd</sup> Generation RLV, are that the payload costs will be a factor of 10 less expensive and it will be a factor of 100 safer than the current Shuttle with an operational date of 2010. The current program is actually planned out to 2040, leading to a 4<sup>th</sup> Generation RLV that is 1,000 times less expensive and 20,000 times safer than the current Shuttle. The timeframe of the present paper is 10 years; thus the concentration in this section will be primarily on the 2<sup>nd</sup> Generation concepts. Note that the current Shuttle is denoted as the 1<sup>st</sup> Generation RLV, even though it is only partially reusable.

### **Background**

The current state of the art in reusable launch vehicles and the U.S.'s premier launch vehicle is the Space Shuttle (albeit only partially reusable), which was first launched in 1981. Since that time several studies have been performed to define both reusable and expendable new launch vehicles. NASA began a serious initiative in 1994 originating from the Access to Space study in which NASA was given the responsibility for developing reusable launch vehicles and the Air Force responsibility for expendable launch vehicles. NASA decided the overall concept with the greater payoff but with more risk was a fully reusable single-stage-to-orbit (SSTO) vehicle. Also, any new operational vehicle should be a commercial venture with NASA assisting in technology development. From this beginning two X-vehicles were started in partnership with industry to help develop the technology such that a decision could be made in 2000 to proceed with a commercially viable SSTO RLV to replace the Shuttle. The vehicle designated X-33 began with three competing concepts in Phase I. The concepts were a vertical-take-off vertical-landing (VTVL) vehicle proposed by McDonnell Douglas and two vertical-take-off horizontal-landing (VTHL) vehicles: a winged vehicle proposed by Rockwell and a lifting body proposed by Lockheed. Lockheed's lifting body concept was selected and became the X-33 vehicle. This vehicle will fly a sub-orbital trajectory reaching a Mach number of approximately 13. As originally proposed by Lockheed, the X-33 would be a scale prototype of their actual RLV named the VentureStar.

At the same time, a smaller scale flight vehicle denoted as X-34 was begun in partnership with Orbital Sciences, with the major objectives of studying rapid turnaround and airline type operations, which selected a winged vehicle with a planform similar to the

shuttle. The vehicle would be launched from an L-1011 before firing its rocket engine to reach Mach numbers from 4 to 8. More recently the X-37 vehicle, awarded in competition to Boeing, was added to the technology base. This vehicle is a lifting body, which will be launched by the Shuttle or an expendable launch vehicle, will reach low Earth orbit and reenter similar to the Shuttle. The new technologies for the X-37 encompass reentry technologies and orbital operations.

There are two additional X-vehicles which were not directly funded by the Space Transportation Program but do impact the technology and possible concept selection for future generation vehicles. One is the X-38 vehicle, which is developing technology for a reusable Crew Return Vehicle (CRT) for future use on the International Space Station. The X-38 is a lifting body and uses a guided parafoil for landing after the high-speed direct reentry. The other vehicle is the X-43 (from the Hyper-X program) which will provide flight data for a hydrogen-fueled scramjet at Mach 7 and 10. The vehicle possesses an airframe integrated propulsion system similar to the former National AeroSpace Program (NASP) vehicle. The technologies and vehicle concepts from the described X-vehicle programs will influence the new Space Transportation Initiative.

### **Current Status**

There are several significant changes in the current space launch initiative from the original Access to Space study. The first requirement is that the full reusability of the vehicle must have a factor of 10 reduction in payload launch cost. Second, while safety has always been of first priority within the agency, this is the first time that actual factors of increased safety (100x) have been defined. Third, a much wider range of concepts can be proposed and considered as viable candidates. The vehicle must be fully reusable but it does not have to be a SSTO vehicle. Therefore, new two-stage-to-orbit (TSTO) concepts and also Shuttle Derived concepts are possible. As part of the Integrated Space Transportation Plan there will be at least two concepts competitively selected as large X-vehicles in 2001 fiscal year, and smaller technology flight demonstrations throughout the program. The new date for the selection of the concept for the 2<sup>nd</sup> Generation RLV is 2005 and will be put into operation in 2010.

The safety requirements primarily impact the method of providing crew-carrying capability. Several concepts are being proposed to meet the crew safety requirements and generally involve separation of vehicles. For instance, the crew compartment is integral to the main vehicle but self-contained, or the crew compartment is a separate vehicle attached to the outside of the main vehicle. In either case, a separation of vehicles occurs in the event of an emergency threatening crew safety. The aerodynamics of such a separation, which potentially could occur anywhere from a low supersonic to hypersonic flight condition, must be accurately defined to insure a safe separation. Furthermore, the

flight abort conditions for the increased safety requirements will require improved aerodynamic performance over a much larger flight envelope than developed in the Shuttle program or previously considered.

As mentioned, the X-38 vehicle is a technology demonstrator for an emergency Crew Return Vehicle stationed at the International Space Station. However, within the current Integrated Space Transportation Plan there is a decision point in 2003 as whether to develop a Crew Return Vehicle (CRT), a Crew Transfer Vehicle (CTV), or a Crew and Cargo Transfer Vehicle (CCTV). Concepts for the three different missions may include the X-37, the X-38, or the HL-20 (a previously studied lifting body concept). The vehicles could be launched by an expendable launch vehicle or the RLV and perform small cargo and crew transfer as well as an emergency vehicle at the Space Station. These concepts may be the one selected as the externally attached vehicle discussed in the previous paragraph.

Technologies are being studied that could impact the selection of an overall vehicle concept. Launch technologies include catapult launching (similar to a plane launched from an aircraft carrier) or maglev (magnetic levitation launch with magnetic fields) as ground-based launch aids in first stages of multi-staged vehicles.

The development of advanced high-temperature materials is being conducted for the thermal protection system (TPS). Current RLV concepts are generally blunt configurations in order to reduce the aerodynamic heating during the entry phase of the mission which impacts the type and weight of the TPS. If such materials can be developed with sufficient temperature resistance then it is possible that the leading edges of the concepts could be made thinner leading to a higher lift-to-drag vehicle with increased cross range. This would lead to an entirely different class of vehicle requiring definition of high performance aerodynamics and an even more critical examination of transition to turbulent flow.

Any RLV concept is a highly integrated package dependent on many space technologies. Aerodynamics and aerodynamic heating are both enabling technologies critical to the design of any RLV. The aerodynamic performance establishes whether the vehicle will fly, and the aerodynamic heating sets the TPS requirements establishing whether a vehicle will survive. The Langley Research Center has been a major partner for atmospheric flight mechanics in all of the X-planes. Langley is the designated lead center for "airframes" and "atmospheric flight mechanics" within NASA's space transportation program.

## **PLANETARY EXPLORATION CONCEPTS**

This category of vehicles includes those vehicles that travel through the atmospheres of planets or moons of the planets or Earth reentry after scientific visits to other celestial bodies, i.e., planetary missions requiring aerodynamic performance and

heating analysis for design of the spacecraft. As will be discussed, in recent years aerodynamics is being used for orbital spacecraft as well as direct entry probes.

Until recently, the state-of-the-art was that an orbiting spacecraft was placed into orbit by retrofiring jets after the transit travel to the planet. This required weight for the jet gas thus increased the launch weight and weight carried in transit. Entry probes [Apollo, Pioneer Venus probes, the Galileo (Jupiter) probe, Viking probes (Mars), and Pathfinder (Mars)] were blunt configurations with high drag required to decelerate the high entry velocities to about Mach 2 where a parachute was then deployed for further deceleration before landing. The probes were released from an orbiter spacecraft (or carrier bus) prior to the spacecraft going into orbit.

NASA has renewed the planetary exploration program under the "Faster, Better, Cheaper" mantra which replaces a few larger missions with many inexpensive missions. With this renewal there are recent, current, or planned missions which rely on aerodynamics rather than retrofire for success of the mission. These missions use aero-assist technology such as aerobraking where the spacecraft or carrier bus dips slightly into the planet's atmosphere hundreds or thousands of times over months for the required velocity decrement to go into orbit, or aerocapture in which the velocity decrement is taken with a single deeper pass through the upper atmosphere in a short period of time for orbit insertion. Both aerobraking and aerocapture require aerodynamic performance, stability analysis, and heating analysis in the transitional flow regime between free-molecule and continuum flight mechanics. If an entry probe were part of the mission, then it would enter from orbit at a lower velocity than from a high-speed transit velocity. The trade off in a mission is whether the weights associated with aeroassist technology, such as thermal protection material from increased heating, is lower than the fuel weight of retrofiring.

## **Mars Missions**

Mars is the largest exploration program with NASA committing to fly a mission during every launch window opportunity, which occurs every two years. The long-term view includes a crewed mission. There are other missions of which those of importance to aerodynamics and heating are sample return entries to Earth such as Stardust (interstellar and cometary dust) and Genesis (Sun solar wind). In 1997 the Mars Global Surveyor was the first to use aerobraking for an operational spacecraft. This may become the standard for all future Mars orbiters including the satellites for the Mars telecommunication network. Aerocapture has not been used to date; but, is being considered for the Mars orbiter portion of the Mars Sample Return Mission and for the human exploration of Mars including the Mars entry and the Earth return. Aerodynamic configurations with lift-to-drag in the range of 0.3 to 0.7 are being studied which include elliptically-blunted raked cones, blunted large-angle cones at angle of attack, ellipsled (elliptically blunted cylinder), and straight or bent

biconic or triconic shapes. Extensive studies of aerodynamic performance, stability, and heating characteristics are required to design aerobraking vehicles for human exploration to Mars. The Langley Research Center is the lead center for aeroassist technology

With a maturing Mars program it is becoming necessary to consider two new technologies which could impact the required aerodynamic performance. These are precision landing and hazard avoidance. In the past we were satisfied just to land in the general area. Now we want to avoid hazards that may destroy the lander or severely impact the mission and we want to land at a precise point on the planet. Being able to land at a precise location is an enabling technology for manned mission where the vehicle must land near the operational base but not hit it. The entry vehicle will require improved aerodynamic performance and guidance systems for these technologies to be successful.

### **Other Missions**

For detailed study of other worlds that have atmospheres, one option is to maintain vehicles aloft in these atmospheres to conduct scientific research. A vehicle that is able to move while aloft has a much greater ability to uncover knowledge about these worlds. The requirements for such vehicles are heavily dependent on knowledge of the extraterrestrial atmospheric composition. These concepts could take the form of “flying” vehicles, such as the proposed Mars Plane, or “floating” vehicles, like sensor-laden balloons or parachutes. Vehicles such as this could be used to study the gas giant planets, Mars, or Venus. One key to research in this area is to accurately use the knowledge of the atmospheric composition to perform adequate analysis, simulation, and experimental testing. At present, computational modeling has not compared well with experimental results, due to different shear-layer and separated-flow predictions. The possibility also exists to utilize larger flyers with highly flexible wings. The biomechanics of using inflatable or tensioned-fabric cords for this application still need to be addressed. Finally, whatever the final configuration for the flyer/floater, it must be designed for efficient storage during space transit, survivability during atmospheric entry, and deployability when on station.

### **Gas Giant Dirigible/ Bathyscaphe**

The gas giants of our solar system (Jupiter, Saturn, Uranus, and Neptune) and to a lesser extent Titan have very thick atmospheres and extremely high pressures on their surfaces. The best way to initially study these planetary atmospheres would be with balloon or dirigible carried instrument packages carried fairly high in the atmosphere at a safe level of pressure. High Reynolds number unsteady flows need to be better understood for these programs.

In addition to the high floaters, it may be possible to send instruments to much greater depths in the atmosphere, and for some cases, even to the surfaces. For these

cases, Bathyscaphe-types of carriers are needed. In addition, the interior of Jupiter's moon Europa may be mostly liquid water. If a Bathyscaphe with instruments was placed below the ice surface, it could explore this huge volume of water. The hydrodynamics of such vehicles might be greatly different than in Earth's ocean, so studies might be needed to examine such flows as might be encountered.

## **NON-AEROSPACE APPLICATIONS**

NASA's could leverage their expertise in aeronautics and space to advancing non-aerospace applications such as ground and water transportation systems. Although not a transportation system, many "Environmental Systems" could also benefit from NASA's discovery and technology development programs. Application of NASA technologies to non-aerospace applications has traditionally happened through spin-offs of focused and basic research programs.

Today many of the roadblocks to "general transportation systems" that are imposed upon NASA are largely political. Many agencies have isolated themselves through budget and manpower requirements internal to that agency, including NASA. The state of the nation's highways and roadways gives new meaning to gridlock. The aging highway systems are in dire need of a paradigm shift. The opportunity to develop alternatives to roads may relieve the staggering gridlock in and around our large cities by moving people via mass transportation systems and personal air highway systems. The debate regarding mass transportation systems will continue and be difficult to sell because of the freedom that a personal vehicle provides. A paradigm shift in this area will be driven by costs and future limitations set by environment and safety regulations. The technology to develop a safe, quiet, and environmentally sound air highway system will happen. What do we need to do to make it happen sooner than later?

Non-aerospace technologies can be categorized into four groups, Ground, Water, Non-traditional Air, and miscellaneous applications. It can be noted that some applications can be multi-functional or have applications in two or more of these categories.

Ground vehicles include automotive, trains, motorcycles, trucks, and buses. Water vehicles include ships, submarines, torpedoes/missiles, hydrofoils, sailboats, and even jet-skis. Non-traditional air applications include bird flight (biomimetics), smart bullets, aerosols, internal engine compartment cooling, nuclear cooling systems, advanced mixing systems, and flight in different atmospheres. Examples of several miscellaneous applications could be weather control systems (tornadoes & hurricanes), pollution detection systems (rivers, smoke stacks, biohazard tracking), energy systems (wind turbines, water turbines), safety systems (wind brakes, parachutes), biomedical systems (heart valve and blood flow systems or other non-Newtonian fluids), and sports (runners, skiing, sky diving, etc.).

### **Ground vehicle applications**

NASA's involvement in ground vehicles has been limited due to the automotive industry focus on style rather than efficiency. Only until recently has the industry been required to meet government regulations on fuel efficiency, thereby giving some emphasis



to aerodynamics. While Henry Ford proposed roadable airplanes as early as 1940, the status of the nation's highway systems may be the catalyst needed to make them a reality. The ability for the nation's automotive industry to utilize NASA's technologies has been, in general, untapped. Passive porosity, unsteady aerodynamics, aeroacoustics, and vortex control are several areas that potentially have application to the future of ground vehicles.

### **Water vehicle applications**

Developing specific technologies related to platforms such as ships, submarines, and underwater weapons have typically been left to DOD and the shipbuilding industry. Today's water vehicles, particularly water munitions, are evolving into multifunctional vehicles. Examples include vehicles that swim undetected for awhile then fly to a specific destination. To develop such systems, NASA could collaborate with the DOD to make an impact. The commercial water applications such as hydrofoils, sailing ships/boat, personal watercraft, etc. could see development in the areas of increased speed, efficiency, load capacity, maneuverability, reduced noise, and safety. Unsteady aerodynamics and hydrodynamics are key areas for such development.

### **Non-traditional Air vehicle applications**

Non-traditional air vehicle applications are areas that NASA is best suited to provide expertise because it closely resembles research that NASA has already committed to. The advent of smart materials that are lighter and stronger gives us the opportunity to rethink speed, size/scale, and shape. New materials, microelectronics, and communication systems make previous impossibilities a new reality. While steady state aerodynamics have been developed to the edge of maturity, our unsteady aerodynamic and acoustic interaction knowledge base across the speed range is beginning to develop with many unanswered questions. Designer fluid mechanics is being proposed to replace conventional control systems. However, accurately scaling the unsteady 3-D microstructure and predetermining the appropriate interactions are not possible today. To develop micro-aircraft or machines that fly in other atmospheres will require a greater understanding of scaling to low Reynolds number at very high speeds.

### **Biomimetics**

Biomimetics is simply the engineering of a system or process that is inspired by and imitates nature. The philosophic view is that there is no need to reinvent the wheel for every innovation. Also one can note that: Nature runs on solar energy. Nature recycles everything. Nature fits form to function. Nature curbs excesses from within. Nature taps power to the limits. By looking at existing systems in the natural world, a researcher may benefit from the 60-140 million years of evolutionary enhancement that has gone into a

system. Biological systems have the greatest untapped potential to revolutionize how we design, build and use future space systems. They are quite simply the most robust and efficient systems in the known universe.

NASA Langley would be ideally suited for such a role. While five of the ten NASA research centers are primarily focused on space research and enhancement, NASA Langley has been known more for its structure and material research, along with its aeronautical and fundamental research activities. To incorporate biomimetics into its current research arsenal would be an easy task for NASA Langley. The basic infrastructure of computing, chemicals, power, and building facilities are already in place. With its research focus, biomimetic programs could begin immediately in the areas of biologically inspired materials, structures, and aerodynamics such as self-assembling, amorphous structures, and flapping wing flight technology. Continuing and broadening the effort could establish NASA Langley as a biomimetic paradigm pioneer. Using nature as a model, Langley could shift its own infrastructure into an environmentally and ecologically balanced entity. The result could be a facility capable of supporting itself on its own power and causing little to no harm on the environment through biologically inspired power production and pollution safe practices. By instituting a biomimetic research paradigm, NASA could enter into partnerships with the DOE, Dept. of Agriculture, DOT, and the EPA. NASA would not only show that it was interested in space but the Earth as well.

## **Environmental Systems**

Applications of aerodynamic technologies to “Environmental Systems” can range from wind turbine aeroacoustics, pollution detection, unsteady wind loading on buildings, biological warfare (application, prevention, and detection), and weather systems (e.g. tornadoes alleviation). New partnerships would be necessary with DOT, DOE, NOAA, DOD, etc. Advances in materials and active flow control systems will open doors to enhancing mixing that could be applied to internal combustion engines, as well as the cooling systems used to manage the automotive and/or aircraft cooling systems.

The fluid mechanics of many biomedical systems (blood, digestion, etc.) can also be addressed by CFD and measurement technologies developed by NASA. Miniaturization of probes applied to active flow systems has spin off applications in many biomedical fields.

While many opportunities exist for non-aerospace applications of the aerodynamic technologies that NASA can develop, it will require manpower and resources that the agency/center/AAAC may not have. It is important to have the critical mass of people and/or resources that can focus on the aforementioned opportunities, or the probability for success is at low risk.

## DISCUSSION

Perhaps one of the reasons that aerodynamics is incorrectly considered a mature science by some is that aerodynamic solutions to problems are often misappropriated in systems studies. Drag reduction due to effective propulsion-airframe integration is often book-kept as a specific fuel consumption reduction and, therefore, credited to the propulsion discipline. Drag reduction enabled by increased aspect ratio is credited to structures, because aspect ratio alone is a known drag benefit, but is enabled by structural advances. Our current state of the art has been brought about with a "departmental" approach to aircraft, and integration was often done as an afterthought with any resulting problems fixed on an ad hoc basis.

It should be clear at this point that the field of aerodynamics, while well advanced in many respects is not fully mature in that there are still many unanswered questions to important problems where solutions would be of great benefit. In this paper we have identified areas for research that show promise for providing those solutions. What we have tried to avoid is any great emphasis on specific vehicles. Individual vehicles, platforms, or airframes should be just a focus for demonstrating the benefits of technologies that can be widely applied.

Although understanding physical phenomena and modeling/prediction of unsteady/complex flowfields is essential, much can be learned by intelligent application of many of the technologies described herein. Controlled flight was achieved decades before 3-D Navier-Stokes modeling was available, and we should not fall into the "if the only tool you have is a hammer, then every problem is a nail" syndrome with supercomputing. Applied aerodynamic and acoustic solutions should be pursued concurrently with the development of prediction and modeling tools. This exercise is highly speculative in many respects, but it is based on clear trends in technical developments in other areas as well as on changes in societal values. We have identified areas for research, but we have not offered suggestions on how to do that research.

Looking beyond issues of purely technical nature we can see a number of other issues that affect the ability of researchers to solve the problems outlined in the previous sections. A major recurring theme is the increasing interdependence of different disciplines in the field of aeronautical engineering that is already known for the breadth of its scope. Multidisciplinary design has existed for some time; what is needed now is the ability to perform multidisciplinary research. The need for integrated research to provide answers to complex problems is apparent. What is less apparent is how to facilitate in-depth research that is multidisciplinary in nature within the current management framework. In the same spirit as identifying areas for research without suggesting solutions, we wish to identify areas that require management attention without suggesting solutions. Three broad areas

need to be addressed: resource allocation, organizational structure, and cooperative efforts with organizations outside of NASA.

The most important resource at Langley is the staff. As research becomes more integrated, attention to the allocation of skill mix between specialists, generalists, and managers may become more important. There is no substitute for the highly educated, experienced, and focused researcher who becomes an expert in a field. Langley has a fine history in identifying and developing this type of researcher. What requires attention is the extent to which generalists can be identified and trained, what skills they will need, and precisely what role they will play. Performing the research to enable development of a flexible structure with smart components that uses unsteady flow control for maneuvering may be as impossible with only specialists as it would be with only generalists. We need to develop a systematic way of balancing these competing needs in personnel development and providing the incentives for various organizations to provide the necessary training.

The equipment and facilities necessary for the staff to do the work must also change. The importance of the information technology revolution in determining the direction of the future research should not be underestimated, nor should its role in enabling and performing that research. As computers have increased in speed, the time between successive generations of computer chips has decreased. The ability to keep pace with this change and provide current tools for the researchers then becomes a management problem. The ability to simultaneously test aerodynamics, electronics, materials, and structures is vital to the development of some of the concepts suggested here. Acquisition of new facilities or modification of old ones to meet these new requirements, as well as management of those facilities, spans distinct management entities in the current organization. We need to develop a systematic way to encourage cooperation between organizational entities at Langley in developing facility requirements, sharing funding and responsibilities, and distributing credit for the work.

Depending too heavily on program-based research tends to limit advances to evolutionary steps. Planning and control can be too systematic and too heavily based on easily achievable. Researchers developing revolutionary concepts must take risks and be ready and able to radically change direction or focus quickly, and have authority to make those changes commensurate with their responsibility to achieve results. This is not to say that a researcher should not be answerable for their work. We need to develop a systematic compromise between existing and new programs, and high-risk fundamental research that will provide the technology breakthroughs that could revolutionize the aerospace industry in the 21<sup>st</sup> century.

There are a number of outside organizations with which Langley cooperates in research and some which not only influence the research that we do, but the extent to which that research is accepted. We have no suggestions regarding cooperative research

with universities. Cooperative research with industry is another matter. Recent experience with large programs focused on the immediate needs of industry with little regard for the long-term needs of the country. The need to provide industry with short-term solutions is real and should not be discouraged. Instead it should be placed in proper balance and not allowed to interfere with legitimate medium term and long term research that provides us the ability to meet industry's needs for the future.

In suggesting pursuit of research that may fundamentally change the appearance and performance of aircraft, we must somehow cooperate with the FAA. The AGATE consortium has already provided a perfect example of how this can be done: a cooperative research effort involving NASA, industry, and the FAA from the onset developed a round-robin method for certifying composite materials for flight that will save industry a significant amount of time and money. By involving all interested parties from the beginning, each party could become aware of the needs of the others and satisfy them with a minimum of false starts and wasted effort. We need to develop a systematic way of directly involving the FAA in NASA research at an early stage so that both organizations understand the implications of the work for future regulatory action.

Under no circumstances should the investigation of advanced concepts be limited to a white paper team. Instead it should be an on-going effort by each and every researcher within AAAC. This was formerly accomplished by interaction with industry and academia on a daily basis in the course of doing business. A short-term horizon, brought about by the need to show immediate relevancy to industry, is partly to blame for eroding this process, but we should take care not to let the pendulum swing too far in the other direction, so that some interaction with industry is viewed as "good."

Furthermore, the AAAC should develop a systems approach to advanced aerospace concepts. Setting the stage for developing and following through with advanced concepts requires a multidisciplinary approach. Engaging in existing LaRC efforts (e.g. ASCA/SAB, AVSTPO, and the Chief Scientist) and internal AAAC efforts will be critical in the filtration of many ideas and advanced concepts into ones that we will modify or pursue. This would require both generalists and specialists. With this mix, an open exchange and assessment of ideas would result. Warning: care should be taken as to not increase the burden on researchers without demonstrated commitment of the management to implement recommendations.

Lastly, it is imperative that stakeholders understand the significance of where the state of aerodynamics, aerothermodynamics, and acoustics has been, where it is, and where it is going. In this light, a recommendation is made to provide the necessary resources to create an interactive compact disk with this type of information. If this information (via text, pictures, photos, video clips, and interactive demonstrations) could be

sufficiently captured and freely released, the misperception that aerodynamics is a “mature science” could be properly handled.

### **Advanced Design and CFD techniques**

Some of the ideas presented in this paper might be considered revolutionary, and others are a revisit to ideas initially examined in the 1940's and 1950's with today's technology. Nevertheless, they are a glimpse into the realm of possibilities, and they probably represent the tip of the proverbial iceberg regarding possible alternative designs and technological improvements to current aircraft. In the effort to delineate the best course of action for research we need a powerful screening process. Thus, considerable advancement is required in design tools, computational tools, measurement devices, and wind tunnel facilities.

Aerodynamic calculations have demonstrated that Computational Fluid Dynamics (CFD) can accurately predict the characteristics of high Reynolds number attached wing flows<sup>15</sup>. With state-of-the-art CFD methods<sup>16,17</sup> essentially, interference drag-free engine installations at flight Reynolds numbers can be designed. However, these computational methods cannot reliably predict flows with steady or unsteady separation. In addition, with RANS modeling adequate resolution of high Reynolds number viscous flow over an aircraft configuration requires millions of grid points and hours of computer run time, even with the use of parallel processing. Such computational times are clearly not acceptable for design techniques that can be applied on a routine basis (e.g., a two-hour analysis calculation must be reduced to a few minutes)<sup>18-22</sup>. While advancements in computers and parallel processing strategies will certainly lead to reductions in computational times, such advancements will not be sufficient to provide the necessary computational capability for complex flow problems such as buffet behavior, vortex bursting, and dynamic stall. Powerful, efficient, and robust numerical algorithms will also be needed.

The next generation of design tools will need to have a broad spectrum of flow modeling capability to allow sufficient flexibility in design. For example, flow analysis should be possible with not only linearized inviscid and nonlinear potential flow methods but also the Reynolds-averaged Navier-Stokes (RANS) equations. The RANS equations must be solved with reliable turbulence modeling (i.e., sets of transport equations for turbulence that have clearly defined ranges of application). Eventually, at least some portion of a flow field should be solvable with direct numerical simulation. This level of analysis would avoid the requirement for turbulence and transition modeling, which may not be sufficiently reliable in certain complex flow situations. Appropriate modeling will be needed for both chemically reacting and real gas flows. In addition to these options for flow modeling and analysis, the design tools for aircraft and various other transportation vehicles will need to

have a multidisciplinary capability. Thus, the tools will need to include the effects of aeroacoustics, emissions, propulsion/airframe integration (PAI), as well as the effects of fatigue and life cycle. For a detailed discussion of design tools the reader is referred to the associated White Paper entitled “Advanced Design and Diagnostic Tools”. In order to construct such powerful design tools substantial improvements in physical modeling and computational capability are necessary.

Recent work in numerical algorithms strongly suggest that a factor of 100 speedup in the time required to solve the governing equations of fluid dynamics for stationary flows is possible. This has immense implications with respect to the use of Navier-Stokes solvers in a three-dimensional design process that can be applied routinely. Furthermore, such a fast steady flow solver can be extremely useful in improving the efficiency of unsteady flow solvers for a variety of problems, especially those in aeroelasticity. For example, the dual time-stepping algorithms for computing unsteady flows depend on a steady-state scheme in order to obtain the solution at each time step. These algorithms have the advantage of allowing large time steps and thus improved efficiency for many practical problems in unsteady aerodynamics. There would be a major impact on the general performance of these algorithms with a 100 times faster steady-state solver.

Until now the principal focus in the development of algorithms for fluids has been on stationary flow solvers. However, unsteady flows are beginning to receive considerably more attention. One reason for this is that most real flows have some degree of unsteadiness. In an effort to optimize the design of aircraft, this unsteadiness cannot in general be ignored in computational analysis. Another reason for the growing emphasis on unsteady flows is the role that they play in many active flow-control devices (see White Paper entitled “Flow and Noise Control”). In order to analyze and design flow controls, reliable and efficient unsteady flow solvers are needed. Reliable and accurate unsteady flow solvers can allow the development of flow controls that offer the possibility of achieving revolutionary advancements in the aerodynamic performance of flight vehicles.

Another important issue for unsteady flow analysis is flutter. Flutter involves the interaction between unsteady aerodynamic loading and mechanical vibrations. In order to ensure a suitable margin of safety for the structural components of an aircraft, it is necessary to accurately predict the unsteady forces and moments. At the present time, due to computational expense, unsteady loading for flutter analysis is primarily performed with potential flow methods. Such methods allow transonic aeroelastic analysis for an entire aircraft configuration in a computational time more than two orders of magnitude smaller than that required by RANS methods. However, if there are strong vortical and/or viscous effects, these methods are not suitable. Currently, new techniques are being developed that involve flow modeling with the Euler and Navier-Stokes equations. The prohibitive computing time for unsteady flow analysis is the major limiting factor for practical

use. Recent applications of dual time stepping methods, with multigrid methods for time step solving, offer considerable encouragement in addressing this difficulty. Flutter boundaries have been calculated with numerical algorithms coupling the unsteady Euler equations and structural modal equations. The computational times have been reduced substantially. Still, much greater improvements are needed before these schemes can be used on a routine basis. The new generation of numerical schemes discussed earlier has the potential to advance this capability for flutter analysis considerably.



## CONCLUDING REMARKS AND RECOMMENDATIONS

The perception that aerodynamics is a mature science is flawed. It is true that our capability to design aircraft in spite of our shortcomings has become routine, particularly for cigar shaped vehicles with thin wings. However, upon careful examination, it is clear that many of these shortcomings occur in flight regimes that are plagued with sociological and technical issues that require advances in our capabilities. This is particularly true in environmental issues related to noise and emissions. Moving the current aerospace paradigms to revolutionary air vehicles will require both generalists and specialists. Expanding the AAAC horizons and developing enabling technologies is the only way that a “revolutionary” aircraft will emerge. While it is important not to lose sight of vehicle concepts, it is more important for AAAC to focus on the enabling technologies and the integration of those technologies that will lead to revolutionary aircraft.

The AAAC should position itself to leverage off of the expertise and advances of other competencies and program offices to utilize state of the art enablers for strength, weight, and flexibility. Some of the current enabling technologies that are outside AAAC might include adaptive/self-healing materials and electronics, molecular nanotechnology, smart structures, and seamless, failsafe, broadband universal communication.

To participate in the development of the “Noise Friendly”, “Green Machines”, “Personal Air Cars”, “Crash-less aircraft” or other truly revolutionary and advanced vehicle concepts, it will be necessary for the AAAC to integrate with “aerospace systems” groups such as Systems Analysis Branch (SAB). Examples of current “Advanced Vehicle Concepts” that SAB are working are shown in the appendix. Evaluating the technology roadblocks to these vehicles will supplement the requirements for technology development. However, as a warning, to establish priorities based on current vehicles alone will be short sighted and potentially limit the development of technology enablers that will pay off in the long term.

Prior to making advanced concepts recommendations it is useful to recognize several recurring themes that are basic to the majority of advanced aerospace concepts.

### **Recurring “Advanced Aerospace Concept” themes include:**

- Revolutionary concepts will not be cigar shapes that land and take off as airplanes do today.
- The status of current prediction and design tools is inadequate for developing a revolutionary aircraft. Expanding CFD and CAA to include complex aircraft features that move and are inherently unsteady will be revolutionary (transition, separation, 3-D vortical flows, noise propagation, etc.). Making these tools “user friendly” will give

the designer the benefit of non-linear analysis and more realistic systems integration capabilities.

- Research in both temporal and spatial scaling for micro-, macro-, and mega-vehicles will be building blocks for advanced concepts through the understanding and application of complex physics.
- Need to develop unsteady Aerodynamics and Aeroacoustics enablers for flow control (both active and passive). Micro-, macro-, and mega-flow control techniques are expected to be a major influence on advanced concepts.
- Utilize flow control, shape control, and aeropropulsive control that is quiet and safe.
- Most high-risk research is being done today is for advanced military aircraft. Historically most revolutionary advanced aerospace applications can be traced to military aircraft. NASA's role should be to supplement, augment, support, or lead such high risk military research activities, then capitalize on appropriate applications to be used for civil aviation. We need to develop or enhance our ties to DOD and DARPA activities.
- New propulsion technologies are critical to aircraft across the speed range. The integration into the airframe systems remains a top enabling issue, particularly for supersonic and hypersonic vehicles.
- Multi-disciplinary research requires unencumbered exchange and communications between researchers, regardless of organization.

## Recommendations

### What We (NASA) Should Aim to Achieve:

- Aerospace vehicles that do not crash, ever, for any reason.
- Aerospace vehicles that do not change the characteristics of the atmosphere with chemical emissions.
- Aerospace vehicles that are so quiet they are not noticed by people on the ground (35dB below current technology).
- Aerospace transportation systems that integrate seamlessly with ground transportation systems.

### What We (AAAC) Should Do to Achieve our Aims in the Long Term:

- Develop **good working relationships** with other Langley, NASA, governmental, industrial, and university entities that clearly delineate these aims.
- Develop a **coordinated plan** with other Langley, NASA, governmental, industrial, and university entities that specifies roles and responsibilities.

- Develop the ability and the work environment to perform **multidisciplinary research**, integrating propulsion, structures, acoustics, etc.
- Develop a complete understanding of **flow separation** and separation control<sup>23</sup>. Focused areas of research should include revolutionary high lift systems that will enable quiet and safe take off and landings.
  - ▶ Active and Passive Flow Control
  - ▶ Circulation Control Wings
- Develop a complete understanding of **transition and turbulence**.
  - ▶ Active and Passive Flow Control
- Develop a complete understanding of every aspect of **unsteady flow**, from periodic unsteadiness to unpredictable unsteadiness<sup>23</sup> due to unexpected encounters with (chaotic) atmospheric turbulence.
- Develop a complete understanding of **combusting flow**.
- Develop a complete system of physics based tools for prediction of noise source generation, noise/structure interaction, and long-range noise propagation.
- Develop a complete understanding of interior noise, active noise control, and human perception of noise.
- Develop **experimental facilities** to test integrated concepts<sup>24</sup>.

#### **What We (AAAC) Should Do to Achieve our Aims in the Near Term:**

- Focus efforts on improving conceptual design tools to prevent conservatism from eliminating promising vehicle concepts and to prevent ignorance from promoting bad vehicle concepts.
- Make development and evaluation of advanced concepts a major, ongoing process within the competency. Form a working group to Interface with “Systems Analysis Branch”. Leverage off vehicle concepts to ensure near term expectations are being met but do not sacrifice basic research that will enable long range programs. Infuse SAB with advanced tools and training to improve evaluation of advanced concepts.
  - ➔ Bring in advanced aircraft design course for AAAC to establish a baseline for how airplanes are currently designed and built (should be offered on a regular basis).
- Promote advanced research tools including new facilities
  - ➔ Develop concepts, hardware, and software to enable immersive visualization of theoretical and experimental results.
  - ➔ 1 meter polysonic ( $0 < \text{Mach} < 5$ , high Reynolds number) acoustic wind tunnel
  - ➔ Hypersonic flight replication tunnel ( $5 < \text{Mach} < 18$ ) with meaningful test duration.
- Provide resources (money) controlled at the branch level to facilitate pursuit of new concepts through enabling decision making by the experts.

- Develop advanced CFD algorithms with improved accuracy and reduced computational effort for multiprocessor supercomputers as well as desktop computers.
- Create bridges to cross-pollinate the AAAC and create a critical mass that ebbs and flows as necessary.
  - ➔ Develop a mentoring program with the appropriate incentives to cross train researchers and support personnel to capitalize on experience.
    - ▶ Initial emphasis should be on fundamental fluid mechanics and acoustics
    - ▶ Initial emphasis should be on time-dependent structural dynamics and fluid mechanics
- DO NOT PICK A FEW GRAND CONCEPTS THAT ARE EASY TO SELL WITH VIEWGRAPHS BUT ARE DOOMED TO FAILURE! NASP was a failure because it was never built, but the research it promoted was not a failure. HSCT was a failure because it was never built, but HSR, the research it promoted, was not a failure. Instead, return to the past practice of solving individual problems that arise from pursuit of advanced concepts. The vehicle will be built when research (including concept demonstrators) has solved the problems, not when the date of the last pre-programmed milestone is reached.
- Enabling technology development should include but not be limited to
  - ➔ Steady-state and time-dependent Viscous Flow technologies (including CFD and experimental Reynolds number dependent physics and applied research)
  - ➔ Active and Passive Flow Control technologies (aerodynamic and acoustic)
  - ➔ ESTOL Transport technologies (take off and landing speeds less than 50 knots)
  - ➔ Personal Air Vehicle technologies
  - ➔ Noiseless Vehicle technologies (including ESTOL, personal, and supersonic (boomless) vehicles)
  - ➔ High Performance Vehicle technologies (cooperating and leveraging off of military applications)
  - ➔ Micro Air Vehicles (leveraging off of biomimetics)
  - ➔ High altitude and long endurance Vehicle technologies
    - ▶ may couple to Micro Air Vehicles, Flow Control, and advanced structures
    - ▶ Extraterrestrial exploration
    - ▶ Real gas research
  - ➔ High Speed Vehicle technologies (supersonic and hypersonic technologies emphasizing propulsion integration and combustor flow physics)
    - ▶ Access to space
    - ▶ Agile missiles

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## APPENDIX

### Examples of Current Advanced Concepts

In recent years a variety of alternative or advanced concepts have been considered for the subsonic and supersonic transports. A few examples are given here, and a number of additional ones can be found in the work of LaRC's Chief Scientist Dennis Bushnell<sup>7,8,9</sup>.

#### Very Large Subsonic Transport

In order to increase the capacity of the current airport system, as well as increase the capacity of freighter transports, the design of a very large subsonic transport (VLST) is being considered in both the U.S. and Europe. Aircraft capable of carrying 600 to 800 passengers over global distances are being designed. Technical problems in designing a VLST include satisfaction of aircraft noise requirements, the fabrication of large composite structures, the control of large flexible structures, engine emission requirements, alleviation of a strong wake, and utilization of current airports. In an effort to solve these problems the following technologies will be extremely important: Active control systems, flow control systems, and simple, effective high lift systems.

#### Long Endurance Aircraft

Many missions have been identified for uninhabited aircraft that can fly for very long duration, (weeks, months, years, etc.) at high altitudes. These missions include environmental monitoring, communications, reconnaissance, and weapons platforms. An example of this technology is the Pathfinder. The "Pathfinder-Plus" is a solar-powered, propeller-driven aircraft with a duration of 2000-3000 hours at altitudes greater than 70,000 feet. These high altitude vehicles operate in a low Reynolds number regime where real gas effects are not well understood.



Dryden Flight Research Center EC98-44621-40 Photographed JUN1998  
Pathfinder-Plus with the islands of N'ihua and Lehua in the background.  
Photo by Nick Galante

## Blended-Wing-Body

A revisit to the blended wing body (BWB) idea introduced in the 1940's has produced several transport designs. Generally, these designs consider integration of the engines with the BWB.

- **Benefits**

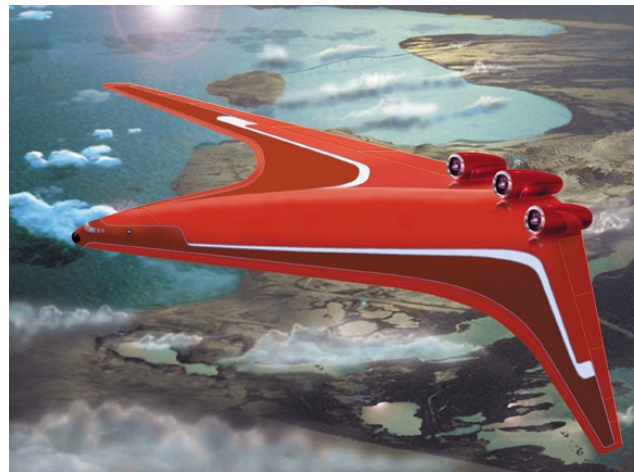
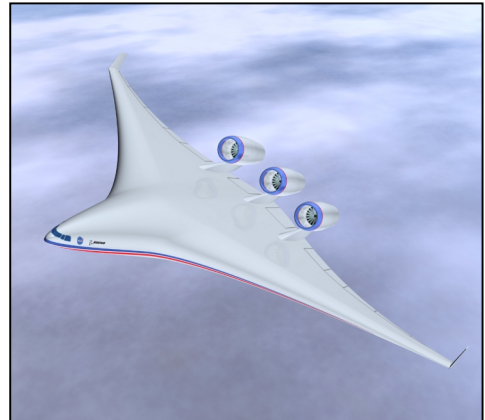
- **Fuel efficiency >20% increase**
- **Weight ~10% decrease**
- **Direct Operating Cost (DOC) ~12% decrease**

- **Challenges**

- **Non-cylindrical pressure vessel**
- **Stability and control at envelope edges**
- **Vortex hazard alleviation**
- **Loading distribution**
- **Propulsion/Airframe Integration (PAI)**
- **Noise propagation**

- **Status**

- **NASA/Boeing project to build 14.2% RPV for S&C work underway. Includes 1% spin tests, 2% rotary tests, and 3% static tests**

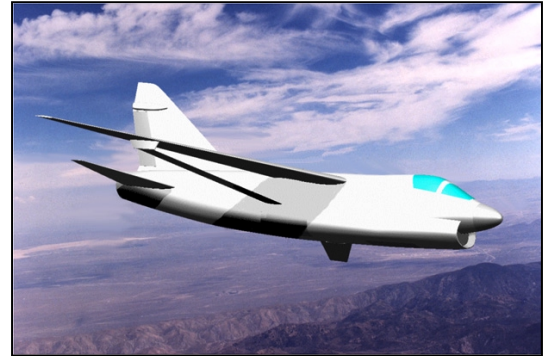




## Strut Braced Wing Concept

One design concept receiving attention involves a strut-braced wing. The wing thickness and sweep can be reduced, which facilitates natural to easily enforced laminar flow with the bracing. In addition, lift to drag ratio (L/D) of 40 (twice as large as current transport values) can be achieved.

- **Benefits**
  - **Significant emissions, weight, and cost reductions (6-12%) due to lighter wing, less drag, & reduced fuel burn**
- **Challenges**
  - **Strut design and integration (aero and structures)**
  - **Propulsion/Airframe Integration**
  - **Laminar flow optimization**
  - **Candidate for tip engine integration**
- **Status**
  - **Currently on hold, but will be addressed in the future**



## Wing Tip Engines

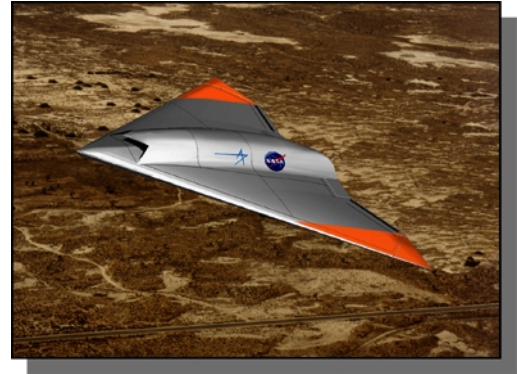
Another concept being examined is the use of wing tip engines. It allows a reduction in aerodynamic drag due to lift and vortex wake. The strut braced wing concept may be a technology enabler for such a concept.



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# Adaptive Vehicle Control

- **Benefits (quantitative analysis pending)**
  - Increased survivability
  - Lower weight, higher performance control surfaces and systems
- **Challenges**
  - Design and integration of innovative aero and structural gadgets that allow full envelope trim and maneuvering for tailless concepts while avoiding surface breaks
- **Status**
  - AVSTPO projects working aero and structures gadgets (RACRSS & Morphing)
  - Phase 1 REVCON project to build RPV pending



## Examples Include:

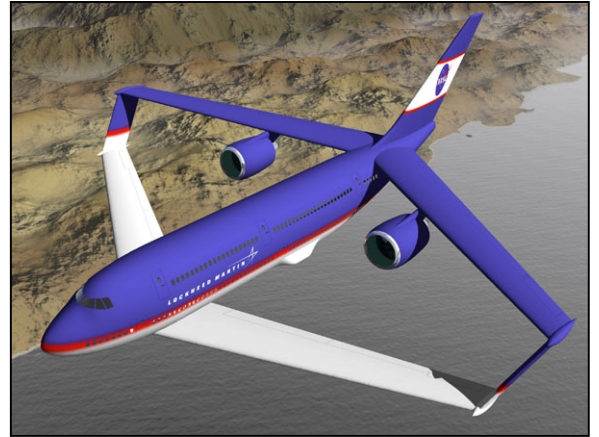
- Oscillatory excitation
- Synthetic jets for pulsed vortex generation
- Passive porosity
- Inflatable Gurney flaps



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## Box Wing

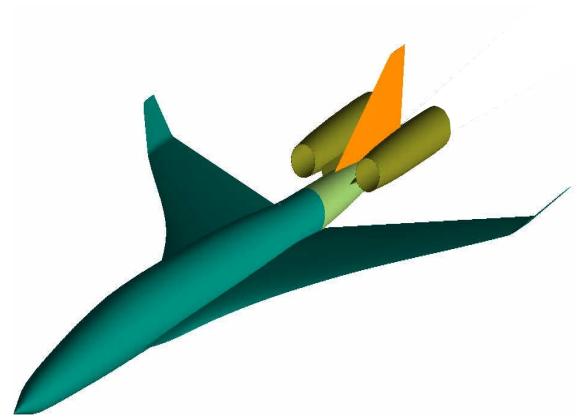
- **Benefits**
  - Modest (~3-6%/available seat mile) benefits in fuel efficiency and DOC
  - ~20% smaller spotting factor than equivalent conventional transport
  - May enable STOL operations and reduced noise footprint
- **Aero Challenges**
  - Simple direct lift system (STOL)
  - Increasing biplane gap to raise efficiency
  - Drag at intersections
  - Propulsion/Airframe Integration
- **Status**
  - NASA work on hold for now
  - Lockheed Martin studying for K $\square$ C-135 replacement



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## Supersonic Biz Jet

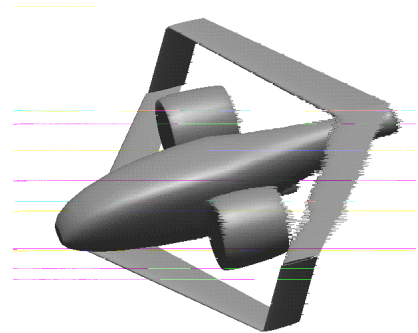
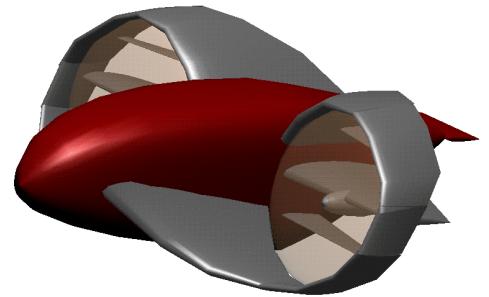
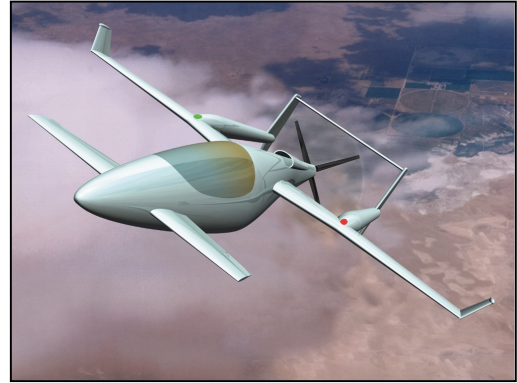
- **Benefits**
  - If sonic boom is low enough to allow overland supersonic cruise, the economics are favorable for development of this class of vehicle
- **Challenges**
  - Sonic boom minimization (shaping, weight reduction, lift tailoring, etc.)
  - Propulsion/Airframe Integration
- **Status**
  - Recently completed near-field boom model tests (favorable results)
  - DARPA proposing a program for similar vehicles



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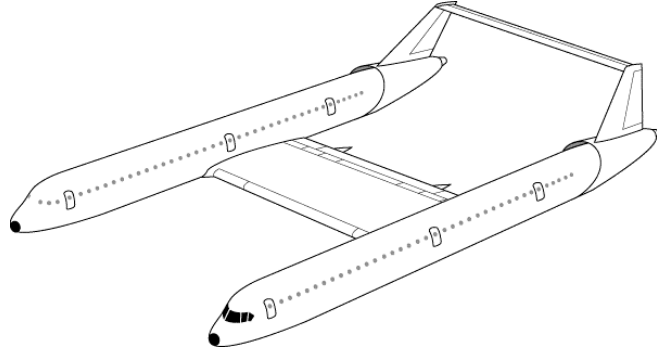
## Personal Air Vehicles

- **Benefits**
  - Major reduction in doorstep-to-destination travel times for the average individual
  - Competitive costs with shared ownership
- **Challenges**
  - Air Safety - Smart systems (aero, control, GNC, etc.)
  - V/STOL for PAV's
  - Propulsion/Airframe Integration
  - Noise propagation
- **Status**
  - Intense studies underway within Advanced Concepts Group of ISAT



## Multi-body Inboard Wing

- **Benefits**
  - Potential for large reductions in induced drag
  - Possibly reduced vortex strength
  - Large capacity with simple systems
- **Challenges**
  - Induced drag reduction characterization
  - Landing gear integration
  - Propulsion/Airframe Integration
- **Status**
  - No current work, but under consideration within Advanced Concepts Group of ISAT





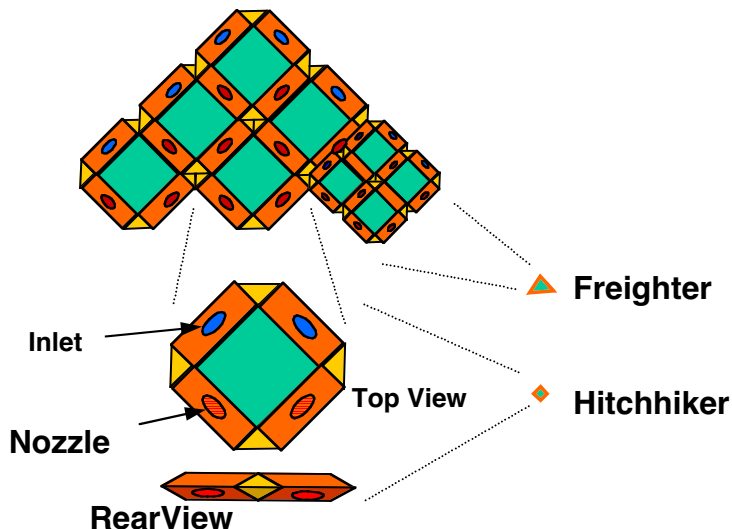
# Automated Package Delivery: A Virtual Memphis

Modular aircraft (freighters) circulate on fixed racetracks between major purchasing “hubs” (above weather and hub traffic). Delivery vehicles (hitch-hikers) detach from the freighters to deliver packages to neighborhood collection centers, while outbound deliveries hitch a ride from the collection center to the freighter & on to their final destinations. Vehicles cross between racetracks to reach other national/international destinations. Robotic collection centers notify customers of deliveries. Freighters are composed of “Lego”-like diamond-shaped delivery vehicles, plus a lead vehicle with management functions, main power, etc. Extensive leverage of SATS, Advanced Structures & Materials, Propulsion, Controls, Aerodynamic, and Smart/Morphing activities.



## Enabling Technologies:

- Wideband communication with the National Airspace System
- “Designer” aerodynamics (make bricks fly)
- Controls (vehicle management, virtual control surfaces, fluidic flow vectoring, ...)
- Advanced materials and structures (electromagnetic glue, recyclable airframe, ...)
- Compact, very cheap propulsion systems
- Systems integration (maglev launcher, package retrieval, security, ground delivery, ...)



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# Intermodal Transports

- **Benefits**

- 2-3X greater profitability for operators due to increased utilization (despite increased trip costs)

- **Challenges**

- Low noise operations to accommodate intermodal configurations (24 hour and 7 day/week operations)
- Structural integration of cargo pods

- **Status**

**No current work, but under consideration within Advanced Concepts Group of Inter-Center Systems Analysis Team (ISAT)**



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## Access to Space - Reusable Launch Vehicles

### X-33

The X-33 is the flagship technology demonstrator in NASA's Space Transportation Enterprise. The X-33 is a half-scale prototype of a reusable launch vehicle (RLV) called the "VentureStar." It will dramatically lower the cost of putting a pound of payload into space from \$10,000 to \$1,000.



### X-34

NASA's X-33 and X-34 rocket planes are suborbital technology demonstrators, operating at speeds up to 15 and 8 times the speed of sound, respectively.



### X-37

The X-37 will be the first of NASA's fleet of reusable launch vehicle experimental demonstrators to operate in both the orbital and re-entry phases of flight. The robotic space plane will play a key role in NASA's effort to dramatically cut the cost of putting payloads into space. Capable of being ferried into orbit by the Space Shuttle or an expendable launch vehicle, the X-37 will operate at speeds up to 25 times the speed of sound and test technologies in the harsh environments of space and atmospheric re-entry.



### X-38

NASA's X-38 technology demonstrator for the Crew Return Vehicle may become the first new human spacecraft to travel to and from orbit in the past two decades, a spacecraft developed at a fraction of the cost of past human space vehicles.



## STOL and VTOL

Rotorcraft, or perhaps VTOL aircraft, poses a somewhat more difficult challenge. STOL Airplanes that land slowly and steeply won't significantly reduce the need for those that hover and land vertically. Using structure to shield noise has significant penalties when thrust is directed downward, so other solutions must be found. Shrouding rotors, at least small ones such as those found on tilt-rotors, may provide a solution. Another approach is to provide adaptive blades that change length or active blades made of smart materials that change twist distribution to alleviate noise while maintaining performance.



### Rotorcraft

Helicopters are rotary-wing aircraft that satisfy a number of transportation, commercial, emergency and military needs in today's society due to their vertical take-off/landing and hovering capability. In general, helicopters travel at a forward speed around 200 miles/hr, have flight duration of two to three hours, and have a range of about 600 miles. They have higher fuel consumption to travel a given distance compared to that required by a fixed wing aircraft. A major problem with helicopters continues to be the noise levels they produce. Some improvement has been made in the forward speed (reaching 345 miles/hr) by introducing jet or propeller systems (compound helicopters). Advancements in materials have made helicopters lighter, stronger, and safer. Innovative technology developments in the areas of flight and flow controls could dramatically improve safety, noise, and aerodynamic performance of helicopters.

### Tilt Rotors

A tilt rotor aircraft is an airplane with the vertical take-off/landing (and hovering) capability of a helicopter. These vehicles have rotors that behave like a turboprop when tilted 90 degrees. Tilt rotor aircraft are expected to provide transportation for short distances (roughly 300 miles). At the present time a tilt rotor aircraft is being built by Bell Boeing (designated the Bell Boeing 609). This vehicle cruises at the speed of 316 miles/hr with a L/D of 8, and it has a range of 870 miles. It will travel twice as fast and twice as far as a conventional helicopter. However, maintenance costs/flight hour may be about four times more than for a conventional turboprop. Reduction of these costs as well as reduction of noise and



emissions will obviously be important issues for the success of the tilt rotor aircraft, especially if the claim by Bell Boeing of revolutionizing air travel is to be realized.

## **Rotary Wing CFD**

At the present time Navier-Stokes computations for helicopter rotor analyses are still far outside the realm of routine calculations. Furthermore, while much progress has been made in developing and improving the efficiency of Euler solvers for inviscid flows, such solvers continue to remain too expensive for routine calculations of helicopter aerodynamics, which frequently involves unsteady flows. Potential flow techniques currently provide the primary methods for computing the aerodynamics of helicopters.

There are five principal areas of aerodynamics to consider for helicopter rotor analyses: 1) Rotor wake prediction, 2) compressible aerodynamics, 3) component and flow interactions, 4) retreating blade dynamic stall, 5) fuselage flows. The first three areas are not viscous dominated, allowing inviscid flow analysis for aerodynamic predictions, which is sometimes coupled with boundary-layer analysis. The rotor wake is the most important issue in the case of hover. Currently, there is no reliable prediction capability for the detailed effect of rotor blade geometry on the wake. For high-speed forward flight, detailed knowledge of the wake is necessary to predict vibratory loading. The structure of advancing rotor wakes is not understood and unsteady loading cannot be reliably predicted. Also, at high-speed forward flight compressibility effects can be quite important. Rotor blade tip flows can be supersonic with shocks, resulting in high drag. Such flows are generally unsteady and strongly three-dimensional. Reliable techniques are not available that include boundary-layer effects and provide coupling with potential methods for global rotor analysis.

Viscous effects can play a strong role in the aerodynamic areas of retreating blade dynamic stall and fuselage flows. The retreating blade of a rotor can experience dynamic stall due to high lift coefficients caused by blade flapping and cyclic input (produced by propulsion). Vortex interactions for retreating blades further amplify this problem. There is no consistent predictive capability for even two-dimensional, let alone three-dimensional, unsteady stall behavior. In the case of a helicopter fuselage, significant flow separation can occur, making it difficult to compute the parasite drag.

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<b>13. ABSTRACT</b> (Maximum 200 words) This report is a review of a team effort that focuses on advanced aerospace concepts of the 21st Century. The paper emphasis advanced technologies, rather than cataloging every unusual aircraft that has ever been attempted. To dispel the myth that "aerodynamics is a mature science" an extensive list of "What we cannot do, or do not know" was enumerated. A zeit geist, a feeling for the spirit of the times, was developed, based on existing research goals. Technological drivers and the constraints that might influence these technological developments in a future society were also examined. The present status of aeronautics, space exploration, and non-aerospace applications, both military and commercial, including enabling technologies are discussed. A discussion of non-technological issues affecting advanced concepts research is presented. The benefit of using the study of advanced vehicles as a tool to uncover new directions for technology development is often necessary. An appendix is provided containing examples of advanced vehicle configurations currently of interest.				
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