NASA/TM–20220009353

Subscale Flight Research Unmanned Aerial Vehicles

Lessons Learned through Vehicle Design, Ground and Flight Test

Gary B. Cosentino
Armstrong Flight Research Center, Edwards, California

July 2022

NASA STI Program Report Series

The NASA STI Program collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the "General" help request type.

NASA/TM–20220009353

Subscale Flight Research Unmanned Aerial Vehicles

Lessons Learned through Vehicle Design, Ground and Flight Test

Gary B. Cosentino
Armstrong Flight Research Center, Edwards, California

National Aeronautics and
Space Administration

Armstrong Flight Research Center
Edwards, California 93523-0273

July 2022

This report is available in electronic form at
http://ntrs.nasa.gov

Abstract

This report provides considerations, best practices, and lessons learned in innovating, designing, building, and testing unmanned subscale flight research vehicles within the 500-lb range. The information provided reflects over 20 years of the author’s experience across a wide variety of aircraft configurations and research objectives. Significant focus is given to vehicle design, ground and flight-test considerations that highlight the importance of gaining an understanding of the maintenance, ground handling, and mission requirements before embarking on the task of vehicle design.

Nomenclature

BWB	Blended Wing Body
CG	center of gravity
FOD	foreign object debris
FTS	flight termination system
GPS	global positioning system
LiPo	lithium-polymer
MUTT	Multi-Utility Technology Testbed
Mil-Spec	military specification
RF	radio frequency
UAV	unmanned aerial vehicle
UCAV	Unmanned Combat Aerial Vehicle

Introduction

Aeronautical research activities, whether governmental or in private industry, many times culminate in the flight testing of an experimental vehicle. This point at which “the rubber meets the road” in research is often an expensive effort requiring specialized personnel, equipment, infrastructure, and unique flight-test locations. The decision to build a vehicle for flight research involves a significant commitment, and, once undertaken, the eventual goal of obtaining useful research data from the flight testing of the vehicle will involve more expense, time, and dedication. Discipline during this undertaking is a requirement, as it is all too easy in the early stage of a research program for practical considerations and realities to overwhelm the initial scientific curiosities. The steps to be taken are as follows: dream and design the vehicle, build the vehicle, perform ground testing, and, ultimately, perform flight testing using the resulting vehicle.

One immediate consideration when beginning these steps is cost. Additionally, the nature of the research and its perceived maturity level may dictate caution in the amount of investment worthy of the maturation process. Often, an answer and way forward are found by choosing to perform the research on a subscale vehicle. Historically, authors have written many papers showing the almost quadratic relationship between aircraft size and cost - specifically, gross weight and cost. An imagined full-scale vehicle prototype fabrication cost might be $200 million, for example, while a subscale, perhaps 10-percent-sized version, just $20 million. Additionally, removing the pilot from the cockpit of the experimental aircraft and placing him in a ground-based remote cockpit further reduces cost and the threat to human life, particularly for research with risky, low-maturity technologies. For these and other reasons, many aerospace research ventures begin with subscale vehicles that are remotely piloted or controlled, keeping the cost within the scope and bounds of the available funding and risk tolerance.

This report looks back over the steps of dream and design, build, ground testing, and flight-testing several subscale vehicles over the past 20 or so years, and examines some of the great (and not so great) decisions that were made along the way, including the successes and failures of various approaches, lessons learned, and recommendations for those who will take similar steps along this path in the future. The report references in some detail those vehicles and flight-testing efforts specific to the author's experience. Opinion, based on example and experience, is found throughout. The intent is to provide general guidance and constructive suggestion toward similar design and flight-testing efforts in the future, where these may be applicable.

Background and Scope

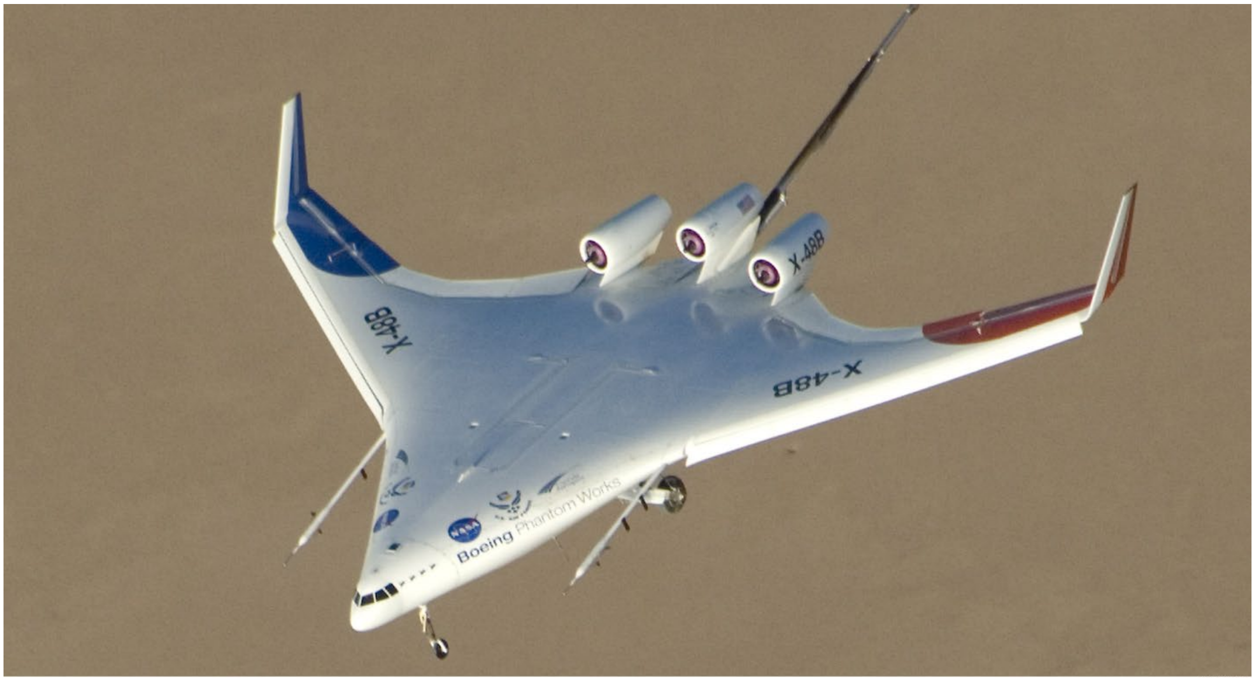
This report draws heavily upon the author's experiences with several subscale research unmanned aerial vehicles over a timeframe of more than 20 years. These vehicles specifically include the X-36 Tailless Fighter Agility Research Aircraft (The Boeing Company) (Chicago, Illinois), shown in flight in figure 1; the Perseus (Aurora Flight Sciences Corp.) (Manassas, Virginia) and Altus (General Atomics Aeronautical Systems) (San Diego, California) high-altitude-long endurance unmanned aerial vehicles (UAVs); the X-45A Unmanned Combat Air Vehicle (UCAV) (The Boeing Company), shown just after fabrication completion in figure 2; the X-48B and C Hybrid or Blended Wing Body aircraft (BWB) (The Boeing Company), shown in flight in figure 3; and, most recently, the X-56A Multi-Utility Technology Testbed (MUTT) (Lockheed Martin) (Bethesda, Maryland), shown in flight in figure 4. The author has also worked with many subscale research aircraft on the lower end of the size, weight, and cost scale, which leveraged radio-controlled model aircraft technologies. This lower end of the size spectrum is ideal for the lowest-cost, fastest-turnaround research projects with minimal risk of loss and damage. This report addresses considerations and experiences in the vehicle size range of approximately 20 lb (small radio-controlled models) to as much as 11,000 lb (UCAVs), however, the emphasis is on the mid-range of this spectrum: vehicles in the 500-lb range (the X-48 BWB and X-56A MUTT). Large, sophisticated UAVs such as the Global Hawk or Predator military aircraft are not discussed, but it is the author's hope that some of the design considerations and lessons learned contained herein can be applied to this very large class. It is also the author's hope that this report will be most useful to those just beginning the design process of a subscale aircraft, and helpful also to the subsequent flight-test planning process.


220015

Figure 1. The X-36 Tailless Fighter Agility Research Aircraft in flight over Edwards Air Force Base (Edwards, California).


220016

Figure 2. The X-45A Unmanned Combat Aerial Vehicle.



220017

Figure 3. The X-48B Blended Wing Body aircraft in flight over Edwards Air Force Base (Edwards, California).

220018

Figure 4. The X-56A Multi-Utility Technology Testbed in flight over Edwards Air Force Base (Edwards, California).

Neither fault nor criticism is implied in the specific examples discussed herein; all aircraft designs suffer limitations and constraints, even under the best of circumstances and conditions. No budget, in terms of dollars or time, is unlimited, and compromises and omissions are inevitable. Ideas for improvement, however, have been noted and are discussed; the intent is to aid future designs, flight-test plans, and evolutions of future research and operational vehicles. It is hoped that this report can serve as a “checklist” of considerations and recommendations that designers and flight testers of future research aircraft can refer to for generalized guidance and helpful reminders during the design and fabrication process.

Design Considerations

This section presents some design considerations for consideration early in the dream and design, and build process. Much of this information is from the realities of working with the aircraft mentioned above, including difficulties encountered along the way, and the resultant repeated thoughts of “if only it were designed this way…”. Again, there is no intent to criticize or second-guess work performed by people who did the best they could within the constraints they were under. The author provides examples of shortcomings and difficulties that were encountered, and offers ideas and options for alternatives that should be easy to incorporate into new designs, provided they are considered early enough in the process. At the end of each subsection, key “takeaway” points are noted as bullets to reinforce important items for that topic for future designers and integrators of subscale research unmanned aircraft.

Aircraft Size and Weight

Extremely successful research UAV aircraft such as the X-36 Tailless Fighter Agility Research Aircraft, the X-48B and C Hybrid or BWB aircraft, and the X-56A MUTT, have spanned the size and weight range from 500 lb to 1250 lb. Future vehicles in the 350- to 1500-lb weight class are a “sweet spot” for research in UAV design. In this weight and size class, fabrication costs have historically been in the $20 million range, with engineering and design adding perhaps another 50 percent to this figure. Costs can be kept manageable while the resulting vehicle remains at a size that can provide scalable data - in some cases, dynamically scalable data - in a representative flight regime with reasonable flight durations and with reasonable data acquisition capabilities onboard. Larger scales become expensive, but often smaller scales result in vehicles that can carry only very cursory instrumentation and operate within a very limited flight envelope.

Propulsion options for vehicles in this size range are readily available. Great success has been had using hobby-class turbojet engines, which provide reliable propulsion at very reasonable cost. Some negatives can include poor fuel efficiency, which for this size and weight class (with limited fuel capacity) can result in short flights. Additional options include gasoline- or heavy-fuel-powered reciprocating engines turning propellers; these are also readily available at low cost from the large model aircraft hobby industry. These types of engines offer much-increased fuel efficiency, albeit with additional complexity and airframe vibration. At the smaller end of this class, electric motor propulsion is a viable option, especially if noise or vibration are design constraints. The relative power density using battery or fuel-cell power generally limits flight duration.

Other considerations need to be taken into account early in the design phase; for example, if an aircraft design is destined for a particular flight-test site, it would be wise to consider the facilities at that site; hangar sizes, hangar door sizes, transportation requirements, runway and airspace constraints, and ground test requirements. Those facilities should be investigated and assets noted as possible. The project team for an aircraft designed with a wingspan that is two feet wider than the width of a door through which it must pass in the future will be faced with some challenges.

In terms of cost, various studies have shown with some consistency that aircraft design and fabrication cost is a strong function of gross vehicle weight. As such, gross vehicle weight should be a prime consideration during the early vehicle sizing and preliminary design process. Generally speaking, the prospective research aircraft should be sized to be as small as practical while still able to execute its research mission at relevant altitudes, airspeeds, Reynolds numbers, and dynamic scaling parameters.

- Decide early in the design process what size aircraft will best match research objectives while remaining affordable.
- Be sure that the aircraft size and performance characteristics are a good match for the prospective flight-test site.

Aircraft Construction Materials

Modern construction materials and methods offer a wide range of options. Composite materials such as fiberglass and carbon fiber are quite prevalent, however, they present unique challenges in terms of accurate weight prediction, as well as with regard to structural stiffness and natural frequencies. The ability to detect and isolate damage and impose subsequent repair methods also can be problematic, particularly on all-composite structures.

The author is neither a structural designer nor materials expert. That said, experience and observations made over more than 20 years of subscale research aircraft testing have yielded some generalizations that are offered herein. The first and most consistent generalization is that subscale vehicles tend to be overbuilt, that is to say, very strong and therefore heavier than they need to be. The structural design process seems to be to design to worst-case loads, and then add a not insignificant amount of margins and safety factors on top of these worst-case loads. This approach seems to apply not only to the basic aircraft structure, but also any internal bracketry and fasteners. The greater the percentage of composite (versus traditional metallic) structure, the more “overdesigned” these vehicles turn out, owing understandably to the uncertainties and lack of materials history with these newer materials. This conservatism in design and fabrication produces robust structures that appear to survive even minor crashes (which is good), but which carry around, for their entire useful life, a penalty in weight and performance or flight duration (which is bad). Those margins and factors of safety that are applied to a new design should be considered and discussed before the commitment to a structural design is made, taking into account the purpose of the research, the risk posture one is willing to take to achieve it, and the life expectancy of the research aircraft.

Another generalization that can be made is that “field removable” parts of the structure (for example, removable wings) can be problematic unless carefully engineered. There is probably no more critical joint on an aircraft than the point of attachment of the wings to the fuselage (or, more generally speaking, the centerbody). This criticality exists not only in terms of consideration of strength, but also with respect to structural modes and natural frequencies. The wing-to-fuselage attachment is never completely rigid; this joint is the source of unique structural characteristics propagating through the flight-test phase, particularly if this joint is separated and removed frequently and its stiffness is not repeatable. For example, the stiffness of this joint might be a strong function of the tolerance fit of the bolts or other fasteners used, and to what torque specification they are tightened. Depending on the research objectives, this variance can be critical. Structural modes and natural frequencies identified during ground vibration testing (GVT) can be critical to the design of the flight control system, for example. If this joint is disturbed after the determination of these modes, it is possible to suffer some shift in frequencies unless the wing-to-fuselage joint is carefully designed and built to be insensitive to assembly variations. Of course, removable wings are often unavoidable. Designing as rigid and repeatable an assembly process as possible for “field removable” components will help minimize unwanted variation in the structural soundness and rigidity of the research vehicle.

- Consider the purpose and risk posture for the research life expectancy of the research aircraft before choosing the construction materials and methodology (tooling, high versus low-temperature materials, et cetera).
- Consider assembly points and removable parts of aircraft with respect to rigidity concerns.
- Don’t overbuild the aircraft - the extra weight will penalize the entire duration of the flight-test phase!

Aircraft Reference Points ("Golden Rivets")

All too frequently subscale research aircraft are conceived and designed without very careful thought given to physical reference points (reference planes) being provided as an integral part of the structure such that physical measurements with respect to design reference axes can be made. For example, center-of-gravity (CG) measurements require some knowledge of, and ability to measure, the longitudinal axis inclination with respect to the gravity vector. Because subscale research aircraft often take on unique design shapes to meet unique flight research objectives, it can be a challenge to measure; and therefore, determine when the aircraft is level. If considered and provided for early in the design, this problem can be resolved and may be as simple as placing a calibrated, precise digital level on a reference flat surface that was designed to be in perfect alignment with the body axes. That is, typically aircraft are weighed and balanced with their longitudinal axis perfectly level with respect to the floor (or to the plane of the measuring scales). This method is critical! Perhaps this level reference surface is external, or possibly it is contained within the structure of the aircraft and made accessible using an access panel to place the digital level upon it. As long as the surface of the level reference is somewhat readily accessible, it will serve the purpose of accurate weight and balance (and therefore CG determination) well.

This requirement for accurate CG measurement is the minimum; this concept can be easily exploited during the early design phase by creating multiple reference points and surfaces in the structure of the aircraft that provide consistent points of reference and known locations for any number of research purposes. Just a single reference plate of appropriate dimensions can provide angular measurement of all three (roll, pitch, and yaw) axes. Known reference locations (so-called "golden rivets") can provide consistent and reliable measurements of distances relative to the structure of the aircraft, useful for locating instruments, accelerometers, gyroscopes, and other devices when their utility is dependent on knowing precisely where they are with respect to other components or structures within the aircraft.

Closely related to this topic is consideration given to providing lift points for the aircraft. Very often it is useful (and sometimes it is required) to be able to lift a research aircraft - for reasons ranging from setting the brakes to suspending the aircraft for structural modes testing during GVT. In fact, locating a single lifting point, such as a threaded insert into which a screw eye can be fastened, can be extremely useful for a physical check of the CG location, without calculation or concerns about scale accuracy and resolution. Locate this threaded insert at the designed or ideal CG location of the aircraft, lift the aircraft just an inch or two off the ground from this point, as see immediately how it in fact does balance. Figure 5 shows the X-36 Tailless Fighter Agility Research Aircraft being lifted by designed-in lifting points.

- Designed-in structural reference points or surfaces are essential; design in a level reference at a minimum for accurate CG measurements.
- Consider lifting points for the aircraft, particularly with respect to future ground testing requirements.

Figure 5. The X-36 Tailless Fighter Agility Research Aircraft being lifted by designed-in lifting points.

Fuel Quantity, Fuel Tanks, and Flight Duration

Experience with subscale research aircraft has shown a very consistent pattern of operating limitations due to insufficient fuel supply, particularly when using hobby-class turbojet propulsion methods. Given the volume-cubed reductions of subscale aircraft, fuel volume (and location) should be carefully considered early in the design process. Three of the four aircraft mentioned in the introduction carried a minimal fuel quantity. The consequences were seen during flight testing, when research missions were terminated almost universally due to reaching the “bingo” fuel state (amount of fuel in which an aircraft requires to safely land at launch site) rather than because all of the planned test points or maneuvers had been completed: flight-test phase objectives were sacrificed, or more flights were flown than were originally envisioned. Subscale research vehicles are often less reliable than would be a production aircraft; more flights translate to more risk of losing the aircraft. Thus, early aircraft layout should prioritize reserving adequate fuel volume and locating the fuel with careful consideration to CG travel as fuel is burned off.

Reasonable research flight durations are approximately one hour. Typically, subscale flight vehicles fall short of this target - sometimes by more than 50 percent - due partly to insufficient fuel volume, and partly due to the low fuel efficiency of subscale propulsion methods (particularly miniature turbojet engines). On each of the research vehicles with which the author has had experience, soon after flight testing began and the flight duration of the aircraft became apparent, thoughts started to turn toward where onboard fuel should be stored. Fuel volume should be identified and quantified and compared to the expected fuel burn rates of the chosen propulsion system early in the design phase to avoid an over constrained capacity. If calculations indicate significantly less than a one-hour flight duration, allocating more volume for fuel should be considered.

Success has been had using custom-made soft-walled, bladder-type tank designs, which can be made-to-order to fit a unique shape inside the aircraft with good volumetric efficiency. Experience has shown a strong preference to this type of drop-in, pre-manufactured tank as opposed to attempting to fuel-seal a compartment inside the structure of the aircraft. Thoroughly sealing a compartment inside an aircraft structure, whether a composite structure or traditional metal structure, is a difficult task, particularly if the access to the inside of the designated volume is limited. Access panels must be provided; the subsequent sealing of these is difficult. Although this approach to providing fuel tank volume has the one advantage of completely utilizing the space available within the structure, some leaks can be expected. If these leaks are external to the aircraft, such as through the access panels, they can be managed; however, if any leaks are such that fuel is admitted into other compartments within the aircraft (such as those containing electronic equipment) severe problems can be posed. These kinds of leaks can also be the most difficult to access and reseal. A drop-in, fitted bladder-type tank does compromise some available volume but can save severe complications down the road with the elimination of fuel leakage.

When using a rigid-wall integral tank that is part of the structure of the aircraft and fuel quantity (and therefore flight duration) is limited, an auxiliary, fuel tank with easy connect/disconnect to the aircraft fuel tank vents will help maximize fuel quantity for flight. When fueling the aircraft, fuel is allowed to fill to overflow, thus adding fuel to the external tank. Engine start and ground operations then can be conducted with the engines drawing fuel from the auxiliary tank, and allowing the aircraft fuel tank to remain completely full. When ground operations are complete, the auxiliary tank can be easily disconnected from the fuel tank vents, the wheel chocks pulled, and the aircraft released for taxi and takeoff with a completely full fuel tank. This method might appear to introduce additional required processes, but if fuel quantity is marginal and flight-test duration is at a premium, the extra time and trouble might be well worth it. Note that the “ground operations” tank concept is not possible with a soft-walled, bladder-type tank, as the suction will pull in the tank walls rather than pull fuel from the auxiliary tank. Figure 6 shows examples of rigid-walled (white) (Aero Tec Laboratories Ltd (ATL) (Ramsey, New Jersey) and flexible-walled (tan) (Jet Tech, LLC) (Eagle River, Wisconsin) fuel tanks.

Figure 6. Rigid-walled (white) and flexible-walled (tan) bladder-type fuel tanks.

Fuel tank pickups and vents, and their locations, are also deserving of some thought. Pre-manufactured bladder-type tanks typically have manufactured-in provisions for fuel pickup, but their vents are usually just a fitting (provided on top of the bladder) that needs to be plumbed and routed appropriately by the aircraft designer. Fuel pickups, by definition, usually reside submersed in fuel continuously, with the attendant deterioration. Fuel pickup tubes should be metallic (aluminum, or, preferably, stainless steel). Soft materials such as rubber-based or plastic fuel tubing may be used for a short time, but if these types of materials are expected to serve inside a fuel tank for longer than a year, they will likely need to be replaced because they will eventually fail. For tanks that are not expected to be serviced or accessed except in the case of failure, aluminum or stainless steel fuel pickup tubes are best. As well, at the tip of each pickup tube, it would be wise to have some sort of a coarse filter or screen to prevent any loose foreign object debris (FOD) or other debris from blocking the fuel flow and creating an engine power loss. If an aircraft design has multiple engines, it would be wise to have multiple fuel pickups.

Fuel tank vents should be on the bottom surface of the aircraft. Vents located atop the aircraft invite fuel spillage and the resultant damage to painted surfaces, fuel intrusion into avionics compartments, loosening of any taped-on hatches or other features, and at a minimum, dirt buildup and contamination. The vents should be forward-pointing to provide mild pitot-pressure to the fuel tank in flight (negative-pressure arrangements should be avoided), and also should be of a size and shape conducive to attachment of an auxiliary “overflow” or “catch” tank which is extremely useful when fueling the aircraft to maximum capacity. Once overflow is seen in the catch tank, the filling pump can be reversed briefly to bring the aircraft fuel state to its maximum but just under the overflow amount.

Fuel quantity measurement also involves a choice of methods. The most direct and accurate are the inclusion of capacitance-type fuel quantity probes. These probes are commercially and readily available and are standard equipment for general aviation aircraft. These probes may be used with either hard-walled fuel tanks or the recommended soft-walled, bladder-type tanks. Typically, the bladder tank manufacturer will install the probe cut to the appropriate length for the tank they are making when the probe is ordered as part of the fuel tank specification. These probes are easy to calibrate, and once properly calibrated, are reasonably trouble-free and reliable. Capacitance-type probes are the best choice for the most consistent and accurate measurements of fuel quantity.

Alternative methods have been used with very good success, such as fuel flow meters and calculated fuel flow from engine control units. Fuel flow meters are also readily commercially available and are used extensively in the general aviation industry. Typically, they come with a calibration “K-factor,” but this factory-specified number is based on general aviation gasoline, which is a lower viscosity fluid than Jet-A fuel. Recalibrating this “K-factor” is generally a good idea if high accuracy is desired; this process can require a somewhat elaborate experimental setup and will take some time. Some of this effort is due to the fact that the flow rate calibration must be performed at the range of fuel flows of interest; building this curve is time-intensive. Care is also required to match the range specified by the manufacturer of the flow meter to the propulsion system of interest. Operating above or below the intended range of the flow meter will result in less accurate measurements.

Many engine electronic control units (ECUs) have sophisticated software that will provide output of the instantaneous fuel flow rate to their engine. Provided the engine manufacturer has spent the required time and effort to calibrate this calculation, this value can be used with good success, and was very successfully used on the X-56A MUTT. The JetCat turbojet engine ECU provided the instantaneous fuel flow rate at all throttle settings via serial RS232 messages. This instantaneous flow rate, when properly integrated, does a good job of providing the fuel quantity remaining throughout the course of a flight. This method, however, is not always so accurate; choosing to use this method, although it is the simplest and requires no quantity measuring hardware or instrumentation, requires careful accuracy checks before it can be used with confidence, especially if there is no other fuel quantity measurement with which to cross-check values.

Whatever the chosen method of fuel quantity measurement, checks of that method should be made as the research flight program progresses. Checks can be performed by measuring the aircraft weight before and after a flight, and comparing this postflight weight to the quantity calculation method chosen.

- Design-in sufficient fuel capacity; target a minimum of one-hour flight duration at typical test conditions.
- Locate fuel mass appropriately with respect to CG and CG shift during flight considerations; consider the appropriate range of static margins to be tested with respect to fuel tank placement.
- Consider the type of fuel tankage to be integrated into the design; drop-in bladder type tanks often are the most trouble-free.
- Consider fuel quantity measurement techniques; a capacitance-type quantity probe yields the most reliable indications once accurately calibrated.

Aircraft Handling and Transport Considerations

The research aircraft discussed herein suffer many disadvantages compared to full-scale aircraft, this assertion is particularly true in the area of aircraft handling and transportation.

Typically, the aircraft will be stored or hangared at the flight-test site and then need to be transported to the actual runway or other area from where it will be operated. Traditional methods, such as taxiing for long distances or towing with a ground vehicle would likely put excess strain on the reduced-scale landing gear components. Experience has shown that it is best to transport the aircraft to the flight-test location using a travel trailer. This method of transport greatly alleviates stress and wear on the landing gear components, and ultimately likely reduces the transit time to and from the flight-test location. Consideration thus should be given to the transportation requirement early in the design process, including the design of the travel trailer. That said, a commercially produced trailer can sometimes be found that is of a suitable size and capacity. Figure 7 shows the X-56A MUTT being towed on a Triton (Triton Trailers, LLC) (Hartford, Wisconsin) travel trailer.

Figure 7. The X-56A Multi-Utility Technology Testbed being towed on a Triton travel trailer.

Once the aircraft has arrived at the flight-test site, the ground crew might need to manipulate the aircraft into place - not usually a problem for aircraft in the 375- to 500-lb range. Nonetheless, suitable manipulation “handles” or “touch zones” must be provided to prevent handling the aircraft at weak spots. Absent handles or touch zones, ground personnel might grab onto anything on the aircraft that resembles a handle or a grab point; often these points are not of adequate strength for pushing or pulling the aircraft and the aircraft could be damaged. On the X-56A MUTT, the nose boom support structure was unfortunately routinely used to lift the aircraft nose, steer the aircraft around on the ground, or push or pull the aircraft. While the structure served admirably in this unintended role, it was not designed or built for these manipulations and could have been damaged or, at the very least, bent. Additionally, the trailing edge of the vehicle centerbody was another target of ground personnel needing to move the aircraft about on the ground; some of this region was aerodynamic fairing rather than solid structure and could have been damaged. Designers should consider how ground personnel will handle the aircraft in the pre- and post-flight environments and either provide (and clearly mark) areas of the external mold line where pushing, lifting, and pulling are, or are not, acceptable. If necessary, tooling should be designed and built to attach to the aircraft in appropriate locations to serve as handles for ground personnel. For example, a small tow bar or handle could be fabricated to attach to the nose wheel strut or supporting structure for aircraft manipulation, and then be removed once the aircraft is positioned (and thus not add any flight weight). Figure 8 shows the National Aeronautics and Space Administration (NASA) Sensor Integrated Environmental Remote Research Aircraft (SIERRA-B) unmanned aircraft (NASA Ames Research Center) (Moffett Field, California) being towed on the X-56 trailer; Figure 9 shows ground personnel handling and moving the X-36 Tailless Fighter Agility Research Aircraft.


220022

Figure 8. The SIERRA-B aircraft being towed on the X-56 trailer.


220023

Figure 9. The X-36 Tailless Fighter Agility Research Aircraft being handled and moved by ground personnel.

It was mentioned earlier that lift points or a CG check lift point should be considered because their utility will likely be proven during the ground and flight-test phases. Consideration should also be given to the method of moving the aircraft onto the travel trailer. Brute force can suffice, but can be risky in the event that someone loses their grip or stumbles. A better method uses a winch and cable mechanism along with an appropriately designed pull point, on the nose strut or otherwise located on the structure, to load the aircraft onto the tow trailer. Ramps and a winch performed this task admirably for personnel on both the X-36 Tailless Fighter Agility

Research Aircraft and X-48 BWB projects. Brute force was used to load the X-56A MUTT onto the travel trailer, but this operation always proved to be stressful. Once on the travel trailer, tie-downs secured the aircraft for the trip to the runway. Ratchet straps have been used with great success, but in the design phase, consideration should be given to where these straps will attach - the landing gear is an obvious choice, but providing some small hooks or loops for the tie-down straps would be handy and provide for safe transmittal of loads to the vehicle structure.

Another minor but very useful consideration is to incorporate a means of centering and fixing the nose wheel steering mechanism during ground vehicle handling operations. Frequently, the nose wheel steering is held in position only by the associated servomechanism actuator, which can easily be backdriven, causing potential damage to the servomechanism as well as making ground handling of the vehicle that much more difficult. A simple pit pin with a remove-before-flight streamer could easily be incorporated at the design phase; when inserted, the pit pin holds the nose wheel steering mechanism straight and true. This approach protects against damaging forces being sent back through the steering mechanism and servomechanism actuator, and keeps vehicle movements predictable for ground personnel.

Air data probes are delicate and easily damaged, yet they always seem to be located in the most exposed position to incur handling damage. Whether the probes are located on the nose of the aircraft (such as on the X-36 Tailless Fighter Agility Research Aircraft and the X-56A MUTT) or on the wing leading edges (such as on the X-48 BWB), air data probes extend forward of the planform of the aircraft - anyone walking near the aircraft has a good chance of running into one. In the hangar, mitigations are stationing cones or other alerting obstacles around the vicinity of the air data probes. During aircraft movements, or when loading the aircraft onto the travel trailer, protective obstacles must be removed temporarily - at this time the probes are most vulnerable to damage. In the early design stages, there is little that can be done about this problem, except perhaps adding protective covers with "Remove Before Flight" streamers, or taking the large step of making the probe removable from the aircraft. Planned removability is a design challenge, as the probe must be keyed exactly to the supporting structure such that each time it is removed and replaced, it is put back in exactly the same position and angular orientation to the principal axis of the aircraft. The author has not seen this difficult challenge undertaken, but it is offered here at least for consideration; if properly executed it could reduce substantially the vulnerability of this critical piece of aircraft equipment.

- Consider how the aircraft will be transported from the hangar environment to the runway early in the design process.
- Designers should consider how ground personnel will handle the aircraft in the pre-flight and post-flight flight-test environments and either provide (and clearly mark) areas of the external mold line where pushing, lifting, and pulling are, or are not, acceptable.
- Landing gear pins (for retractable gear) and steering pins will make ground handling easier and safer.
- Consider methods for removing the air data probes (or how best to protect them during ground handling).

Aircraft Protection During Ground Operations or Towing

Protecting the aircraft during ground operations or towing is usually considered only as an afterthought, but the topic is a very important one, careful consideration of which will be necessary at some point during the project. As discussed above, air data probes are fragile, so suitable protective barriers must be utilized to protect these probes from personnel walking into them or equipment being moved into them. Stanchions, cones, or sawhorses also make very good barriers as well as visible reminders of the necessity for personnel to exercise caution when moving in the vicinity of the aircraft. Other safeguards and protective equipment are camera lens dust caps, engine dust covers, inlets and exhaust covers, and the like.

Depending on the flight-test location, special care must be given to dust intrusion. Many experimental research aircraft are operated from dry lakebeds or other unpaved or unimproved surfaces. The amount of dust that can be generated from driving or towing an aircraft on these surfaces can be alarming. Without proper protection, this dust will find its way into every crack and crevice in the skin of the aircraft and can accumulate and do damage to anything that is sensitive to its presence. Obviously, small engines of any type can be quickly damaged by this kind of dust intrusion. Fabric covers have been fabricated in the past to address this needed protection, but it was found on two projects that the permeability of the fabric did not provide adequate protection of the fine silt-like dust found on the lakebeds at Edwards Air Force Base (Edwards, California). After transiting from the hangar to the lakebed surface for flight operations, the fine dust found its way through the fabric covers and into the inlets of several engines. The remedy for this problem was to add a second non-permeable layer of protection to cooled engines in the form of plastic bags. Although inelegant, this solution stopped the ingress of the fine dust. Factors such as these are better taken into consideration during the aircraft design process, when suitable protective covers can be made that are able to cope with the likely hostilities to be found on the future flight-test location and its flight surfaces.

- Depending on the chosen flight-test site and the specifics of its environment, aircraft protection during transportation might be essential.
- Engines require 100-percent FOD protection, including against the ingress of fine dust particles; where protection cannot be designed into the vehicle, adding protection post-flight is critical.

Aircraft Hatches and Access Panels

As a practical matter, a research aircraft must enable frequent access to its internal components, be they critical aircraft subsystems or flight data instrumentation and recording components. Internal volume usually proves to be at a premium in subscale research vehicles, thus internal components and instrumentation must generally be scattered within the available allowable space, locating items where they fit as opposed to where they more logically would be placed. Accessibility and maintainability may be a fallout rather than the priority of design tradeoffs. These considerations usually result in numerous access panels and hatches being used to install and maintain these scattered components. How these numerous panels are attached can vary according to whether the panel is deemed “structural” or not by the designers. If structural, meaning that their rigid attachment to the structure of the aircraft is critical to the strength of the design, the panels must be securely bolted down in place with an appropriate number of screws or other fasteners, and as such, the panels would not be quickly removed. Compartments requiring frequent access, therefore, such as those housing vehicle batteries, power switches, or recording media, should not be located under bolted-down, structural panels. More infrequently accessed components, such as the vehicle flight control computer, power supplies, or perhaps a panel covering the compartment where the fuel bladder is located, can and probably should be located under rigidly fastened, structural panels.

That said, when designing bolt-down structural access panels on full-scale aircraft it is common aerospace practice to utilize so-called self-locking “nut plates.” These plates are fixed devices that receive the screws that hold down the access panel and are designed such that they self-lock the bolts in place. A considerable amount of torque is required to both insert and remove these panel screws; often this considerable torque, if using full-scale aircraft nut plates, is too much for the fixed structure that the nut plates are attached to. If the surrounding aircraft skin material is relatively thin carbon fiber or fiberglass, for example, the rivets holding the nut plates in place can exert an excessive amount of concentrated force and can over time and repeated removals and replacement cycles damage the composite skin or fracture it. The excessive holding force of these full-scale aircraft nut plates is simply not necessary and is very often a problem for the maintainers. Short-duration research flights during which the aircraft receives very frequent inspections do not require the holding power of full-scale aircraft nut plates, and to use them can lead to damage. It is recommended that either non-locking equivalents of these nut plates be found, or a tap of the appropriate size be run through the locking nut plates, effectively removing the very high-torque locking feature.

A note of caution: repeated insertion and removal of screws and other fasteners into locking nut plates generates metallic debris that falls from the nut plate into the aircraft compartments below. This metallic debris is conductive and should be considered FOD, especially if the debris falls onto (or into) aircraft electronic components. The creation of this type of debris is perhaps the most serious undesired consequence of high-torque locking nut plates. Removing the locking feature can be accomplished by running an appropriately sized tap through the nut plate, as mentioned above; however, this operation should be conducted before the nut plate is installed in the aircraft, both to spare the skin of the aircraft the torque of the operation, but, more importantly, to prevent the introduction of this metallic FOD into the aircraft. Even with the locking feature removed, there remains a good chance of metallic debris being shed after repeating insertions and removals of screws. This condition should be monitored, and debris periodically cleaned up.

Options for the fastener-head type should be carefully considered for access panels that are deemed structural and that also require frequent removal and replacement. Cross-head screw heads do not wear well under repeated fastening and unfastening cycles. No matter how careful the maintainer is, after a few cycles this type of screw head will be stripped, and alternative approaches will be necessary to remove it; for example, a drill bit might be necessary to remove the entire screw head. This problem isn't often considered or expected by designers, but in practice, it happens. Slot-head screws fare better, but also suffer damage over time. Additionally, if the receiving panel has countersunk screw holes for flat-headed fasteners, slotted-type screws can cut into the countersunk seats and eventually pull though the panel, especially if the panel is made from composites. Hexagonal heads or, better, star-shaped fasteners offer more trouble-free options, and they are available in flat-head configurations allowing flush fastening with less aerodynamic drag. These head types are sometimes difficult to source in the smaller screw and head sizes, but they can be found. On the X-48 BWB vehicles, the replacement of slotted-head screws in countersunk thin composite panels with flat-head, hex-driven screws were found to be an exceptionally important improvement. International Organization for Standardization (ISO) metric (M3) flat-head screws with a hex drive were readily available from commercial parts houses.

Other access panels can be deemed by the structural engineer as "non-structural." The "non-structural." A non-structural panel does not contribute significantly to the overall strength of the aircraft, and therefore can be non-rigidly mounted. Non-rigid mountings can be taped-on panels, for which simple Mylar® (DuPont Teijin Films) (Chester, Virginia) polyester tape is used to secure the panel in place, providing a smooth aerodynamic fitting with no structural strength. Components requiring very frequent access, in particular circuit breaker or switch panels used to power on and off aircraft systems, fueling ports or fill points, removable recording media access, batteries, or other daily access components, should be located under non-structural access panels. Packing tape in fact does a good job of attaching and holding these types of access panels in place; this method has been used with great success in the past. This common tape, however, does not last long, and exposure to sunlight or cold for any period of time weakens it and makes it difficult to remove cleanly. An improvement to this common method might be a simple hinge with a single, twist-to-lock fastener, or even rare-Earth magnets. Such magnets are nowadays readily available and inexpensive and possess sufficient strength, if enough of them are used, to securely hold small panels in place. Whichever method is used, it is important to remember that non-structural frequent-use access panels often contribute greatly to aerodynamics; the loss of one or more in flight could lead to vehicle damage or degradation, or loss of control of the aircraft. A sufficient amount of holding strength thus must be provided, while not to the degree of structural, bolt-down panels.

A final note on the subject of access panels: the size of the opening created when the panel is removed must be large enough to allow physical insertion and manipulation of the components located in the compartment. Consideration should be given to what will be located in the compartment, how it will be manipulated (the methods of insertion and removal through the opening), and the fact that the human hands that will be performing the insertion and removal may not necessarily be very small. Further, once a component is successfully inserted through the opening, presumably it must be fastened down or otherwise secured in the aircraft - the tools required to accomplish this attachment must also fit through the access panel opening. This line of thought might seem like excessive elaboration on a simple subject, but years of experience show these considerations have not always been taken into account. Sometimes design decisions are based on an assumed “lifetime” of the research vehicle; for example, good physical access to internal components and in general, maintainability, are sacrificed or dismissed for a research vehicle that is expected to undergo only a “three-month flight-test program.” Maintainers and engineers working with the aircraft subsequently wish the designers had thought longer-term than that since the flight research phase often, unanticipatedly, continues on for years.

- Access panel design should not be an afterthought; consider accessibility, frequency of equipment installations and removals, and FOD control.
- The retention method of non-structural access panels should not be overlooked. Use of packaging tape is often regretted. Consider other methods, such as quarter-turn latches, Mylar® tape, or magnets.
- Bolt-down structural panels should be retained with wear-resistant bolts such as hexagonal-key or star-shaped heads. Full-scale locking nut plate hardware should be avoided.

Aircraft Control Surface Sealing

For good aerodynamics, low drag, and high control effectiveness, the moveable control surfaces of the aircraft, which are generally placed at the trailing edge of a wing or other body surface, require good sealing at the hinge line. If Installation and removal are also performed at this hinge line, access for this area can be in conflict with a design that also provides integral sealing of the gap between the control surface and the wing. The author has seen various different approaches for design treatments in this critical area. Some involved purpose-designed composite “blades” that bolted onto the wing trailing edge once the installation of the control surface was completed. The X-36 Tailless Fighter Agility Research Aircraft took this approach, as shown in figures 10(a) and 10(b), with great results, although it was costly in terms of fabricating the seals and allowing for their attachment points.

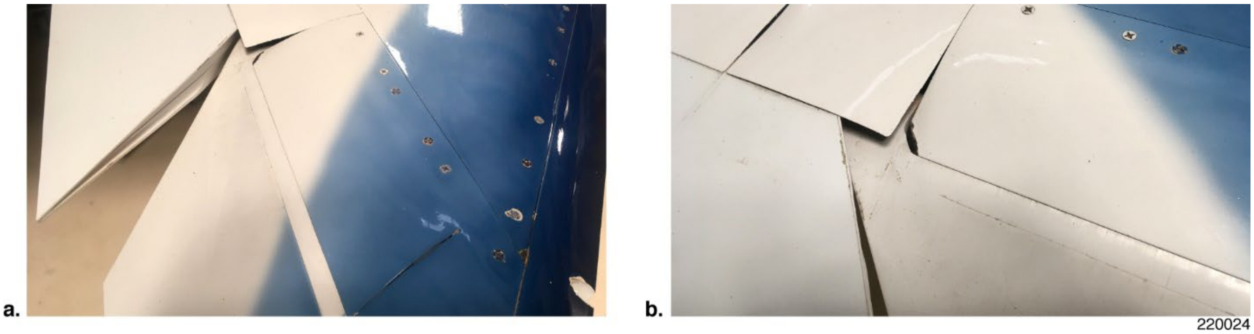


Figure 10(a). The composite trailing edge control surface “blade” seals of the X-36 Tailless Fighter Agility Research Aircraft; and (b). Closeup of the composite trailing edge control surface “blade” seals of the X-36 Tailless Fighter Agility Research Aircraft.

This method resulted in strong, highly elastic seals for the control surfaces wherein even the opposite-side seal, with full control surface deflection in the opposite direction, still maintained contact with the surface. Of course, this amount of elasticity resulted in some preload of the surfaces in the neutral position (equal seal pressure top and bottom), but the hydraulics of the X-36 Tailless Fighter Agility Research Aircraft had no difficulty with this minor additional hinge-moment loading. As the seals in this case were made from carbon fiber, their underside, in the regions that made contact with the control surface, were lined with Teflon™ (The Chemours Company, FC, LLC) (Wilmington, Delaware) tape, thus minimizing friction and abrasive wear.

Should a control surface require removal, the length of seal covering its hinge gap can be removed, allowing full access to the hinge attachments and fasteners. This fabrication effort made during aircraft construction can pay off later in that the seals can be easily removed or replaced.

Another method used on the X-48 BWB was more labor-intensive, but worked equally well at lower airspeeds. In this case, provision for control-surface hinge-line sealing was not made, per se, in the design and construction of the aircraft. Instead, it was intended that seals would be fabricated and installed as a retrofit before the aircraft went to flight testing. The concept was to use two-inch-wide Mylar® strip material to cover the gaps, as shown in figure 11(a); for some areas of the wing and control surface, the strip material had to be bent to apply curvature and preload to ensure the seal followed the movements of the control surface, as shown in figure 11(b). Attachment to the wing was then made using strong double-sided adhesive tape, and then covering the forward-facing step with packing tape.

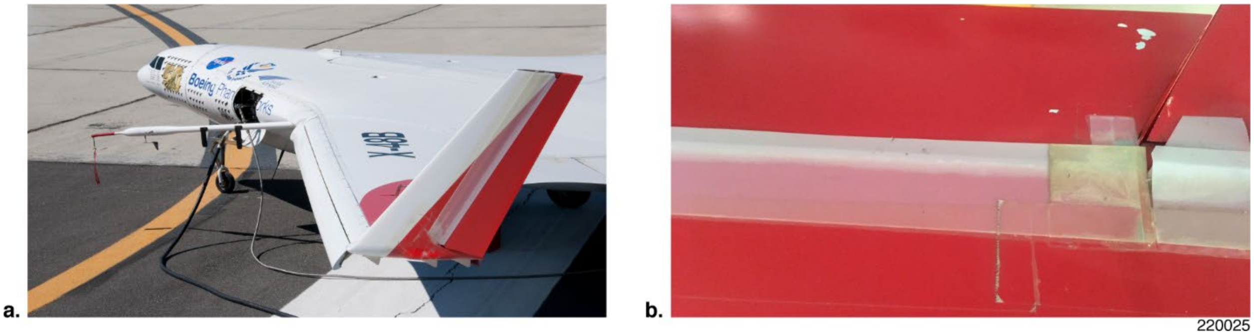


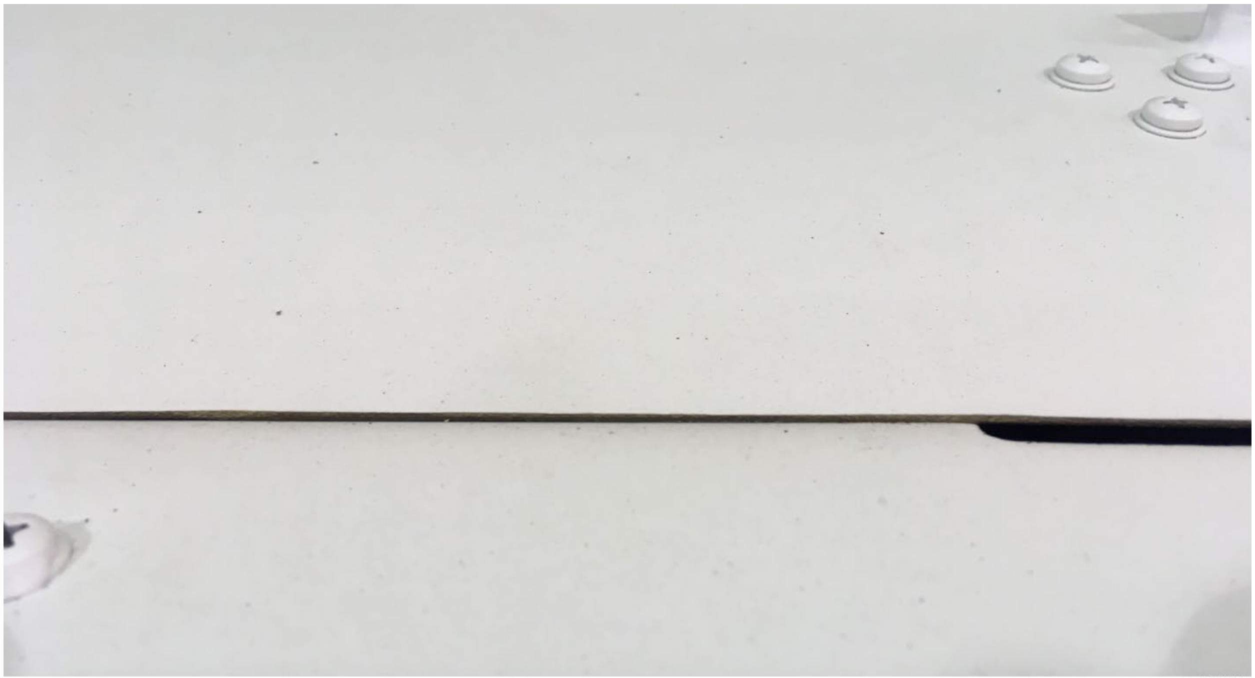
Figure 11(a). Mylar® strip trailing edge control surface seals on the X-48 Blended Wing Body aircraft; and (b). Close-up of Mylar® strip trailing edge control surface seals on the X-48 Blended Wing Body aircraft showing curvature and preload.

This method performed well but was very labor-intensive because each seal was custom-fit to the area of the wing-to-control-surface intersection for which it was intended. Additionally, the attachment being made with adhesive tapes, removal was not as simple as unbolting the seal, and damage to the custom-fitted strip seal was always possible. This approach likely saved cost in the fabrication stages of aircraft construction, but these savings were paid back as these seals were later fabricated and installed at the flight-test site. The seals worked very well, but the author does not recommend this approach.

Another method is the one utilized by the designers of the X-56A MUTT, shown in figures 12 and 13. This method is the simplest and least fabrication-intensive, yet offers good control-surface hinge-gap sealing at lower airspeeds. The trailing edges of the upper and lower wing skins are simply extended past the trailing edge of the wing, creating a pocket wherein the control-surface hinge line is countersunk. When the control surface is installed into this pocket, the upper and lower skin extensions cover a portion of the upper and lower regions of the control surface, thereby creating a seal of the hinge gap.

220026

Figure 12. The X-56A MUTT hinge-gap pocket formed by wing skin extensions.



220027

Figure 13. The X-56A MUTT control surface installed in a hinge-gap pocket.

This method is efficient and requires no additional “custom” fabrication because it is designed into the wing construction method. The seals being fixed, the upper and lower surface skins do not follow the control surface movements; however, if the skins overlap properly and the hinge-node line is properly located within the overlap, the amount of “unporting” when the control surface is fully deflected can be sufficiently minimized.

- The control-surface gap sealing technique should not be an afterthought; it is most efficiently provided for when integrated into the design.

- The aircraft speed regime (dynamic pressure) and control surface hinge moments factor directly into the design of the gap-sealing approach.

Power and Subsystems Control

Depending on the complexity of the aircraft and its subsystems, a smaller or larger number of controls will be needed to apply power to those subsystems in controlled fashion. Once the electrical subsystems are laid out, an interface panel is usually designed to accommodate the resulting number of power controls and other interfaces to the vehicle subsystems. At this point, a choice must be made regarding whether power is to be switched on and off either by toggle switches or circuit breakers. Typically, for example, a flight control computer must be powered-up to allow it time to boot properly before bringing on power to the various subsystems it controls. This procedure is followed, for example, to prevent inadvertent control surface movements or the initiation of radio frequency (RF) transmissions. In fact, because spurious RF transmission is to be avoided in most flight-testing environments, it is a good idea to put RF transmitters on a switch or circuit breaker so that positive control can be exerted over their operation, independent of other aircraft subsystems.

Controlling power to the various subsystems by using aircraft-quality circuit breakers has been used extensively with excellent results and serves two purposes: power can be switched on and off by pushing or pulling the breaker, and the circuit is protected by using the appropriate amperage-rating circuit breaker. These breakers are also relatively compact (up to 30-amp ratings or so) and are designed to be integrated in a row-like fashion and set quite close together. Several breakers can thus control several aircraft systems on a relatively compact panel. The X-36 Tailless Fighter Agility Research Aircraft controlled its rather complex subsystems using 20 such circuit breakers in a very compact panel measuring approximately 4 in by 8 in. The X-56A MUTT has nine breakers as well as other interfaces in a panel measuring approximately 3 in by 7 in. The breakers can be fitted with plastic caps to aid in pulling the breakers to deenergize the circuits. These arrangements have been very successful and efficient in terms of space utilized on subscale vehicles. Figure 14 shows the X-56A MUTT vehicle interface with the circuit breaker panel.

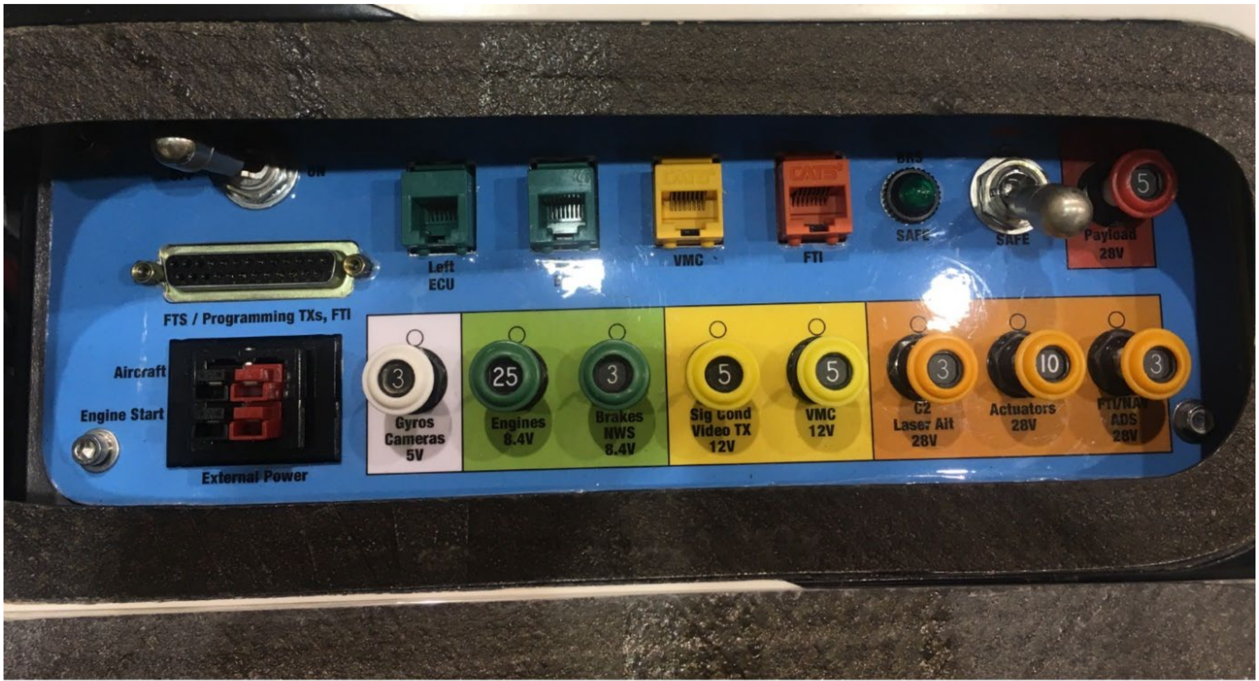


Figure 14. The X-56A MUTT vehicle interface with the circuit breaker panel.

The X-48 BWB aircraft utilized three high-quality toggle switches to control power on three separate power busses, the line of thought being that no one is on board a UAV to reset a tripped circuit breaker. Fuses to protect the wiring and subsystems on the X-48 BWB aircraft were of the fixed, inline type and were not readily accessible nor replaceable. Figure 15 shows the X-48 Blended Wing Body vehicle interface panel.

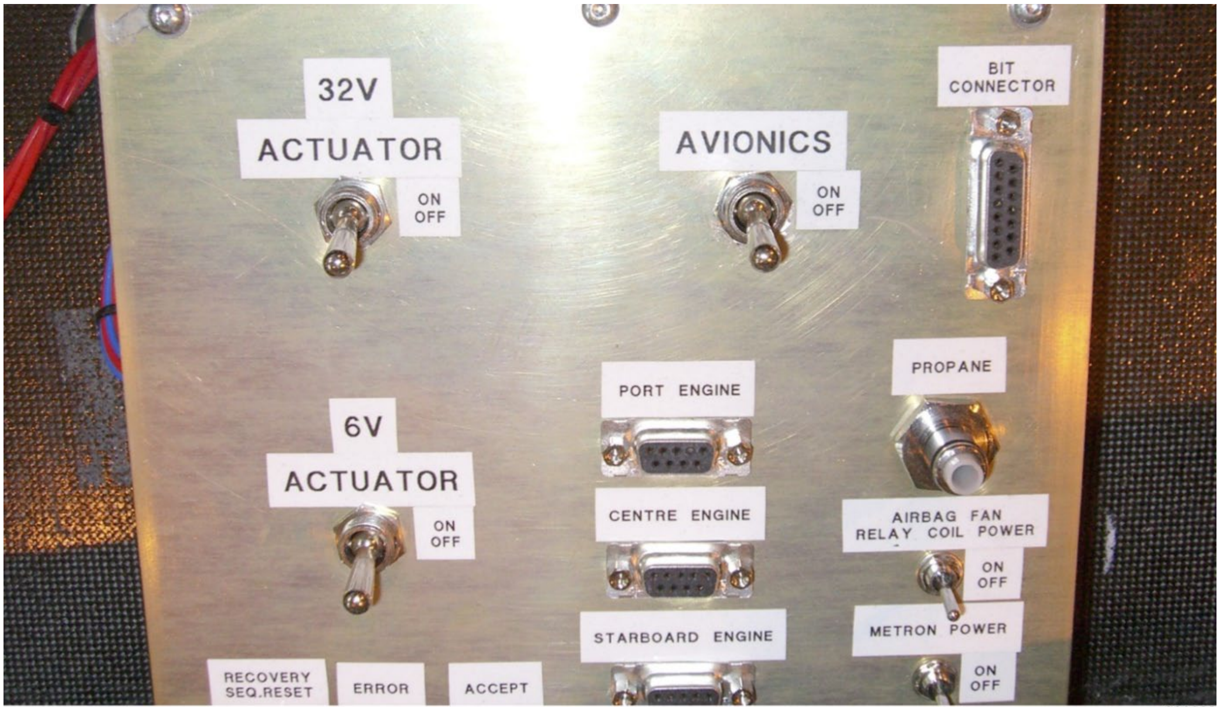


Figure 15. The X-48 Blended Wing Body vehicle interface panel.

The decision to use either toggle switches or circuit breakers to control power distribution on a subscale aircraft design is ultimately a choice of preference or standard practices. The author has seen both approaches work equally well and has never seen an instance in which a circuit breaker has “popped” during flight. There exists, however, an exception to this choice: if the subscale research aircraft is required to have a flight termination system (FTS) to prevent, in the case of critical system failure or loss of command and control communications, the vehicle from departing the designated boundaries of the test range. Power to the FTS must be controlled, per Range Commanders Council regulations, by a lever-locking toggle switch, that is, a switch that requires a deliberate pull to move to the off or on positions. Circuit breakers or fuses are not permitted in the power distribution systems to the FTS.

Other interfaces to the aircraft subsystems, such as serial communications to the flight control computer, diagnostic interfaces, transmitter frequency selection interfaces, software loading ports, and other access between ground support equipment and the subsystems, can be provided on the same power distribution panel and generally via military-type cannon plug or military specification (Mil-Spec) D-subminiature connectors. Mating connectors with pigtail connectors to the various ground supports computers and other equipment are easily fabricated and then conveniently accessed by utilizing the interface panel of the aircraft.

- Both conventional aircraft quality circuit breakers and Mil-Spec toggle switches have been used to control power switching to aircraft subsystems with equal success; select the method with which you are most comfortable.
- Use quality Mil-Spec connectors for electrical connections to the aircraft subsystems; protect against dust and other environmental intrusions that may compromise connectivity.

- Power to a FTS must be controlled by a lever-locking toggle switch; circuit breakers or fuses are not permitted in the power distribution systems to the FTS.

Subscale Aircraft Electrical Power

There are several choices for electrical power for subscale aircraft; these choices are highly dependent on the estimated demands of the electrically-powered systems of the aircraft and the anticipated flight durations. Also, to be factored in are any options for electrical power generation, such as from engine driven generators or alternators, or perhaps from exotic sources such as fuel cells or solar panels. The volumetric efficiency of subscale aircraft being at a deficit, power density will be at a premium and will likely be a key driver on power source choices, especially if the expected (or designed-to) flight durations are extended. A traditional, highly reliable power source is battery power, especially with contemporary modern lithium-based battery chemistries. There are no less than six different types of lithium-based batteries available at the time this document was authored; the most popular and readily available two are the lithium-polymer (LiPo) and lithium-iron-phosphate (LiFe) batteries. Both of these types of batteries possess excellent characteristics for application to subscale research aircraft, and both types have been used with great success.

In the past, nickel-cadmium batteries were considered to be high-energy, and, for very high-energy demands, silver-zinc batteries were the common choice. The backup electrical supply for the X-36 Tailless Fighter Agility Research Aircraft consisted of two arrays of silver-zinc batteries, which were rechargeable but very temperamental and gave their rated power capacity only for a very few cycles. These batteries also had a limited calendar life, whether they were actively used or not. Given contemporary lithium technology, those two silver-zinc arrays could have easily been replaced with lithium-polymer cells, either matching the energy at a reduced size and weight, or providing increased energy capacity at the same equivalent weight. These batteries also would have been longer-lived, more robust, and capable of tens of cycles before noticeable degradation of capacity.

Given that the electrical power of the subscale aircraft is most likely to come from an array of modern lithium-chemistry batteries, if it is also possible to extract electrical energy from the propulsion system, this method can serve to provide supplemental power, thus enabling a reduction in the weight of the battery supply. The X-36 Tailless Fighter Agility Research Aircraft derived all of its electrical power needs from an engine-driven starter-generator, and the battery array supplying only emergency backup in the event of engine failure. The X-48 BWB was, at the other extreme, an entirely battery-powered research aircraft with no on-board power generation capability. The X-56A MUTT was between the two, having engine-driven starter-alternators absorbing the electrical load at higher power settings, and the batteries carrying the load below a certain throttle setting. The battery weight burden carried by the X-56A MUTT thus was reduced compared to what that weight would have been without the engine-driven alternators.

If engine-driven or other sources of electrical power are available on board, some sort of power supply or power management unit will be needed to provide smooth, constant power as the main source transitions from the batteries to the alternative source and back again. The power management unit will also require the appropriate battery charge management circuit if the intent is that excess electrical power be used to recharge the batteries. This method was followed on the X-56A MUTT with great success: seamless continuous power was provided to the critical flight systems regardless of engine throttle setting or the state of charge of the batteries.

The generally extended period of preflight systems checks for the 300- to 500-lb range of subscale vehicles deems it critical to provide accommodation for the application of electrical power to the aircraft from a ground-based source. The power management unit must accept this external power and use it to not only power all aircraft systems during the preflight checks, but also to use this power to either charge or maintain a full charge of the batteries used by the aircraft. Providing for this capability will allow the preflight checks and systems verifications to proceed without hurry, because there will be no drain on the aircraft batteries. This external power can be maintained right through engine start and disconnected only immediately before taxi and takeoff. Again, proper design of the power management device onboard the aircraft will help ensure that these electrical power transitions, from ground power to battery and possibly then to engine-driven generation, is seamless, and no adverse power transients or interruptions are felt by sensitive subsystems (for example, the flight control computer, which must function continuously throughout these operational phases).

Battery chemistry choice will also determine the voltage of the various power busses. All electronic components and other devices on these busses, which may see the full battery voltage, must be appropriately rated. Lithium polymer batteries, for example, allow voltage choices in approximately four-volt increments, the voltage of a fully charged cell being exactly 4.20 V. Thus, a seven-cell pack will present a terminal voltage of $7 \times 4.20 = 29.40$ V when fully charged. Most aircraft-quality (and especially Mil-Spec) components that are nominal 28-V rated should present no trouble with a seven-cell LiPo battery bus voltage; however, depending on how much discharge is seen in the particular use case, near the end of charge this seven-cell battery will dip to as low as $3.0 \times 7 = 21.0$ V. This may be near the lower limit of operational voltage of some 28-V components. In order to buffer this lower limit, an eight-cell pack might be required; however, fully charged it will present $8 \times 4.20 = 33.6$ V to these 28-V-rated components. Depending on the manufacturer's specifications, this voltage might be pushing the upper limit. Care and a systems engineering approach are required during the electrical design phase to ensure that bus voltage levels and component limits, with consideration for margins at the fully charged and depleted-charge cases, are maintained within acceptable ranges. For nominal 28-VDC aircraft electronics, only the 7S or 8S LiPo battery cell configurations are reasonable choices.

Accessibility of the batteries is an important consideration, particularly if LiPo batteries are used. Lithium polymer batteries should not be charged inside the vehicle because of the inherent volatility of their chemistry. Modern chargers safely charge these types of batteries; however, there is always the possibility of failure and fire. Lithium polymer batteries are most likely to exhibit aberrant behavior during charging; thus, it is highly recommended to build in easy access to the batteries, making them easily removable for charging. Additionally, LiPo batteries do not store well when either fully charged or fully discharged, so in the event that a flight operation is delayed, it is best to remove them from the aircraft and place them on a battery charger that is capable of bringing their state of charge to the appropriate storage level.

- Research aircraft electrical power requirements should be estimated with ample margin, before deciding on power sources and on-board generation.
- Ground power provisions should be designed in to avoid depleting the batteries during preflight operations.
- Be certain that the chosen subsystems can handle the voltage of fully charged batteries.
- Lithium chemistry batteries offer high power densities and good lifespans. Be sure to determine how to maintain a battery's state of charge during storage for optimal future use.

Subscale Aircraft Propulsion

There exist many good options for propulsion systems for vehicles in the overall weight range of 300 to 600 lb. These options range from conventional internal combustion (reciprocating) engines (gasoline or heavy-fuel-powered) to turboprop and turbojet engines, as well as electric motors. Choosing a propulsion system is based on many factors, the primary factors being the design of the aircraft, its intended speed and altitude range, and the desired flight duration. Secondary considerations might be, for example, noise constraints, payload considerations (sensitivity to acoustics, vibration, et cetera), ease of propulsion system integration with the overall design, and weight.

The model aircraft hobby industry provides many choices in size and thrust range for simple turbojet propulsion, from diminutive 5-lb thrust engines up to 130 lb of thrust or more. Two of these larger, 130-lb-thrust engines would provide a 600-lb gross weight aircraft with excellent performance over a wide speed range. Turboprop engines capable of turning 25- to 40-in propellers producing as much thrust but at a lower velocity and with somewhat better fuel efficiency are also available. Many of these engines also have the capability of producing a substantial amount of electrical power by way of engine-driven generators or alternators. Generally speaking, these units are fairly readily available in the hobby marketplace and come as complete packages ready for integration and installation. Engine control units are supplied that are very sophisticated for the price point and that control all aspects of engine operation, as well as keeping track of vital engine statistics such as cumulative running time and time histories of exhaust gas temperature (EGT) to provide valuable insight as to the health of the engine as it accumulates service time. Figure 16 shows the X-48B Blended Wing Body JetCat P200 turbojet engine in a nacelle configuration; figure 17 shows the X-56A Multi-Utility Technology Testbed JetCat P400 engine with starter generator in a podded (external) configuration.

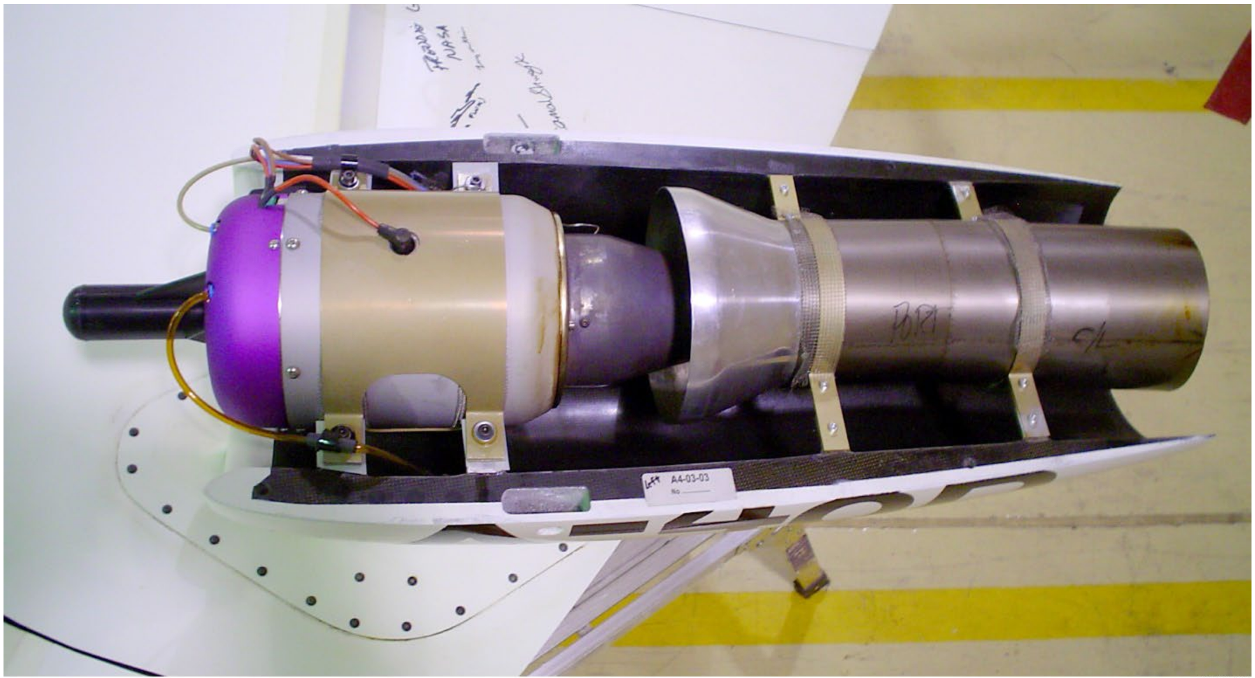


Figure 16. The X-48B Blended Wing Body JetCat P200 turbojet engine in a nacelle configuration.

Figure 17. The X-56A Multi-Utility Technology Testbed JetCat P400 engine with starter generator in a podded (external) configuration.

Slightly more efficient propulsion may be provided by turboprop engines, which are also readily available from the hobby market in several sizes. These engines do pose more challenging integration problems owing to the large-diameter conventional propellers they turn and the rather large exhaust stacks they utilize, but for certain aircraft configurations they might be ideal, because they offer larger static and low-speed thrust from smaller-core engines, and therefore burn less fuel. Figure 18 shows a radio-controlled almost-ready-to-fly 60% Super Cub (Bill Hempel's Team Edge) (Tucson, Arizona) model aircraft with a turboprop propulsion system installation.

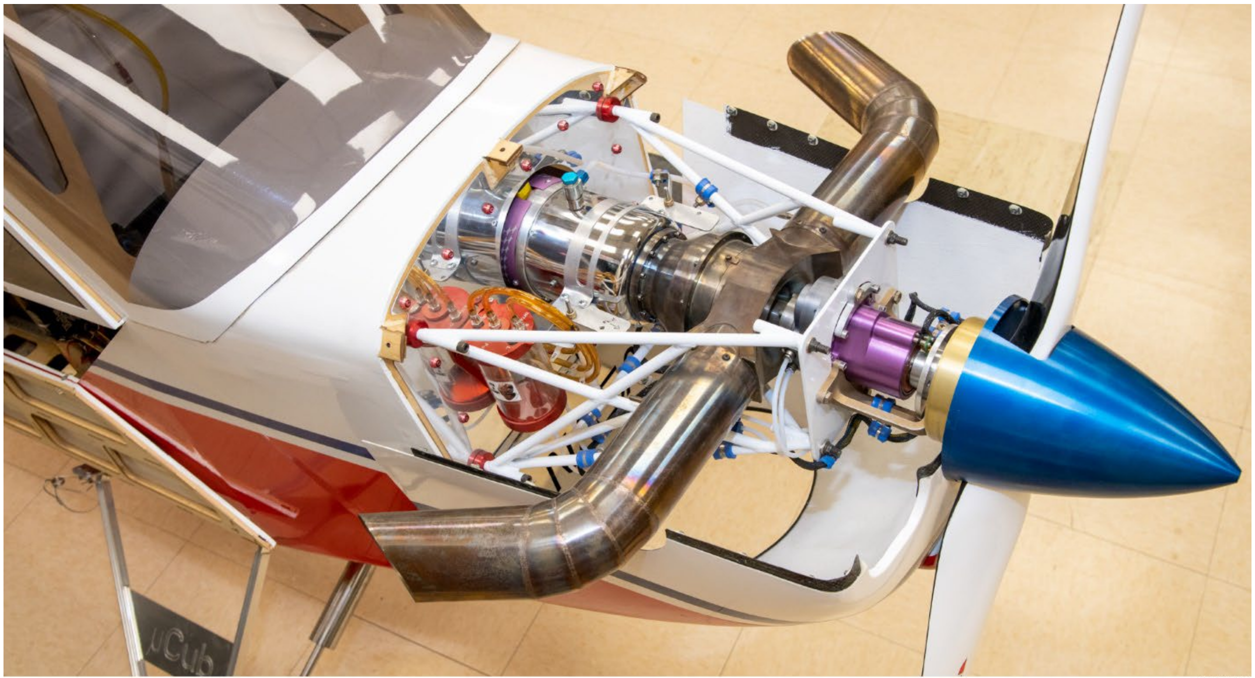


Figure 18. A radio-controlled almost-ready-to-fly 60% Super Cub (Bill Hempel's Team Edge) (Tucson, Arizona) model aircraft with a turboprop propulsion system installation.

There is much knowledge and experience to be gained by accumulating familiarity with the engine and its operation toward building and developing confidence before either committing to the propulsion system or installing the system on the aircraft. A test stand with at least rudimentary instrumentation should be constructed to enable time and experience to be gained with the selected engine (or an engine that is under consideration) - perhaps measure the thrust and fuel consumption and electrical power requirements of the engine, especially during starting. It might also be possible to build the required interface between the engine control unit and the flight control computer, and thus demonstrate positive control by way of the flight software and the engine. It is even possible to explore subtleties of engine operation such as its frequency response to throttle commands (easily achieved by running frequency sweeps through the flight control computer, or external computer) and measuring the ability of the engine to respond to increasing frequency of throttle command. Frequency response data can be very useful in the flight-test phase.

If flight duration is driving factor of the design of the research aircraft, reciprocating internal combustion engines can be attractive, because their fuel efficiency is generally superior to that of turbine engines. There is a developing market for commercial and military UAVs; engines to efficiently power them are becoming more and more available. Gasoline being quite volatile, some applications and usage environments dictate the use of so-called “heavy fuels,” such as diesel fuel or the various grades of jet fuels, which are far safer in terms of flammability. Many heavy-fuel reciprocating engines are being developed and can prove to be very fuel efficient. They do swing large propellers, however, which might or might not integrate well into the overall design of the aircraft. The propulsive efficiency is also therefore optimized for lower flight speeds.

If noise is a factor, electric propulsion is a good choice, whether produced by propeller or by way of ducted fans. Battery weights and capacities will of course be limiting factors, but if the utility or research purpose of the vehicle is noise-constrained, electric propulsion is a viable option in light of contemporary battery technology. Hybrid-electric approaches with embedded, muffled combustion engines turning generators to produce at least a portion of the electric power required are also being studied actively.

- There are a variety of size-suitable propulsion systems available – most are commercial off-the-shelf.
- Flight regime, flight duration, and research objectives should be considered when selecting the best choice for propulsive power.
- Accumulating familiarity with the engine and its operation is important to develop confidence before either committing to the propulsion system or installing the system on the aircraft.

Landing Gear and Braking Systems

The author is by no means an expert on landing gear design, but has developed some experience with, and appreciation for, the subject. Based on this experience, some generalizations and observations are provided for consideration by future designers of similar aircraft.

In the author's experience, well-damped trailing link main landing gear have worked consistently well over multiple platforms. The trailing-link design absorbs landing impacts extremely well, and with some tuning of the damping can provide routinely non-eventful landings. Great success has been had with commercial off-the-shelf mountain bicycle components, such as dampers and spring-shock systems. The sizes of the commercially available mountain bicycle components are fortuitously well-matched to the 300- to 600-lb class of research aircraft described in this report, and many are easily fine-tuned, either by varying the shock strut air pressure or the spring preloads, to give precisely the load capacity and dynamics called for by the research vehicle. These gears are ruggedly designed and well-suited to the type of use they would see in a research UAV of this class.

When the trailing-link design does not integrate well with the overall aircraft design, simple spring-bar type main gear have been utilized; however, attention must be paid to the materials properties and spring constants to avoid undesirable bounce tendencies within the main gear. Spring bars do not have active damping components as do trailing-link designs; damping mechanisms are therefore limited to lateral tire-scrubbing energy dissipation upon aircraft touchdown. This method of energy dissipation is of course not as powerful as hydraulic piston damping and is very difficult to adjust or tune. How successful a simple spring-bar main gear design can be will depend on the overall vehicle design and its takeoff and landing characteristics. For unusual vehicle designs and planforms, flying wings, or research vehicles with stability challenges, a simple spring-bar main gear design may prove to be a disadvantage.

Regardless of type of gear, its placement on the vehicle with respect to center of gravity and aerodynamic center must be carefully evaluated. For example, flying-wing type aircraft have limited pitch control authority to rotate the nose up to a flying angle-of-attack. Having the main landing gear to far aft with respect to CG and/or aerodynamic center can make rotation at takeoff speed difficult, resulting in "pop-up" at high ground speed and the potential of a takeoff stall. Conventional tailed aircraft are more resilient to this condition.

The continually innovative mountain bicycle industry also offers many options that can provide effective braking for the 300- to 600-lb class of research aircraft. Braking components are designed to be very light and robust; braking components from the mountain bicycle industry have provided excellent service in both the X-48 BWB and X-56A MUTT aircraft.

One note of caution on the integration of these kinds of braking components into a research aircraft: the master cylinder, which usually drives a piston to provide braking pressure, does not typically have much travel in terms of linear motion from fully-off to fully-on braking levels; therefore, the method and design of the actuation mechanism for the application of force to the master cylinder piston must be carefully planned. Whether using a linear or rotary-motion servomechanism actuator, a direct, rigid connection to the master cylinder piston will result in very poor proportional control of braking force, because for good resolution, the servomechanism actuator must be allowed to move a good proportion of its full travel. The best way to couple the servomechanism actuator to the master cylinder piston is through some type of spring, perhaps a progressive spring, thus efficiently converting what is inherently a position command of travel to a force resultant acting on the master cylinder piston. The more the servomechanism actuator is commanded to move, the more it will compress the spring, and therefore the more force will be applied to the master cylinder. Overlooking this consideration will result in what pilots refer to as “binary” brakes (brakes that are either on or off), and the commensurate complications in ground handling and post-landing deceleration during flight testing.

- Landing gear design and placement with respect to both the CG and the aerodynamic center are critical to satisfactory takeoff and landing performance.
- Trailing-link designs with well-selecting damping have proven to be excellent design choices.
- Actuation methods for brakes must adequately convert a position command to a force command.

Radio Frequency Equipment

Research aircraft of the type discussed herein typical rely exclusively on RF equipment for connections with ground-based personnel and control stations, including in many cases the link to the remote pilots. As such, these RF links and the associated equipment are of vital importance to the success of the research system and must be carefully considered and designed. Operational considerations are also very important, such as frequency agility and band selection, as well as the ability to interface with the aircraft systems in the absence of RF authorization, for example, in ground testing and troubleshooting activities - the so called, “hard-lined” ground operations.

There are three RF links typically associated with operating subscale research aircraft: an uplink (also known as command and control) and two downlinks, a telemetry parameters stream, and a video stream. The telemetry stream contains all of the health and status indications of the aircraft systems, as well as the research flight data parameters that may be both recorded and also monitored in real time during a flight. The video stream is typically the “out-the-nose” scene to the remote pilot that replaces what the view would be were the pilot sitting in the cockpit of the aircraft. This typical scenario indicates that three separate radio frequencies are required, and these must be sufficiently separated from each other to avoid interference between themselves. Determining the required separation necessitates that an accurate measurement be made of the bandwidth of each of the three RF links so that adequate frequency isolation can be ensured.

Selecting RF hardware for the aircraft requires some knowledge of the flight-test site and its frequency band authorizations. If the site planned for flight testing is known, much time and effort can be saved by using available site assets, as well as selecting airborne equipment within the existing allocations for the site. Fine tuning toward bands or frequency ranges that are the lead used increases the chances of getting specific allocations for flight test sorties. This leveraging can save the project team considerable time, resources, and money by avoiding duplicating assets or equipment that can be borrowed from the flight-test site. For example, often RF components such as transmitters and receivers can be borrowed from the test site, and already are known to be compatible in terms of RF spectrum. Flight termination system components also are sometimes available for loan at the flight-test site, and they usually are already certified and tested; utilizing these kinds of components can relieve the project team of the process and cost of procuring and certifying components. While this practice is not a panacea for integrating range-acceptable systems, it is most certainly an excellent beginning toward that end. Other assets at some flight-test sites are communications and telemetry reception and transmission infrastructure, most notably high-gain antennae with which to track and communicate reliably with a UAV. The National Aeronautics and Space Administration

Armstrong Flight Research Center utilizes two 7-meter (21-ft) high-gain dishes to both receive telemetry and video signals and to transmit uplink commands to an aircraft. The tremendous gain available from these large antennae make solid, reliable communications almost a given. Not utilizing these kinds of assets, which might already be available at a flight-test site, has generally proven to be a mistake. Often new project teams enter the flight-test phase uncertain of where flight-testing will be conducted, and thus attempt to procure and develop their own communications and tracking antenna capabilities. Sometimes this "self-contained" approach is followed because it is the desire of the project team to be mobile, or because the team is planning to perform multiple flight-test campaigns at several different sites. These of course are valid reasons to develop self-contained systems that do not rely on a particular range to operate; however, in other cases, the decision is based, incorrectly, on a perceived attempt to save on the cost of using the range. The idea is to bring communications and data transmission apparatus and not have to pay for time spent using range infrastructure, but for this author, this approach has been seen to yield a false economy. The project budget typically could only produce a transmission system that was barely capable of producing a sufficient link when the aircraft was stationary. Once taxi-testing, or any other moving operations, began, the quality of this low-cost setup quickly revealed its limitations. In similar situations, inevitably time and more money will be spent to integrate the range assets to allow safe flight-testing to begin. The lesson learned is that range infrastructure should be leveraged to the maximum extent possible, to include borrowing equipment if possible, and that a project team should not distract itself with trying to "reinvent the wheel."

Typically, commercial off-the-shelf RF equipment will have a tuning capability within a selected band or range within that selected band. Frequency agility is key when operating in a busy spectrum-competitive environment; tuning the transmitters and receivers quickly once receiving a frequency assignment will aid tremendously in expediting readiness for a flight opportunity. There are generally several ways this specific frequency tuning can be performed, such as dial-type rotary selector switches, jumper wire pre-made connector plugs, star wheel-type switches, et cetera, but the best way is by way of software interface to the pilot's or ground operator's station. Modern RF equipment typically have an RS-232 or other serial interface that allows remote command of frequency selection and whether or not the transmitter is enabled for RF. Utilizing this interface and providing provision for assigned frequencies to simply be selected by the pilot or ground operator will be the most efficient, and allow for last-minute changes that might otherwise cause the cancellation of a flight opportunity. Sometimes a laptop computer can be connected in the field to this RS-232 interface, but this method could cause operational delays. If it isn't possible to provide for remote RF on or off and frequency selection command, then it is best to have the RF transmitters on separate switches or circuit breakers so that the aircraft can be powered for ground tests or troubleshooting without RF transmission clearance. Additionally, manual methods of selecting frequencies should be provided in convenient locations on the aircraft; behind non-structural easily removed panels, external connections, et cetera.

Radio frequency transmitters onboard the research aircraft can be expected to get hot. These transmitters generally do not come with any cooling provisions, and rely on their aircraft installation to provide some means of dissipating the heat they generate while in operation. Locating them in a bay cooled with ambient air while the aircraft is in flight is helpful, as well as mounting them atop some type of heat sink, such as a metallic structural panel of some mass. Clamping an external heat sink onto the transmitter body can also increase heat dissipation. A working solution the author has seen several times is to simply mount commercial heat sink stock onto the RF transmitter, using some heat-conductive grease or compound in between, and then mounting a small muffin-type cooling fan on top of the heat sink to force air into and out of its cooling fins. Even in a non-ventilated bay, this approach has worked very well in maintaining transmitter temperatures within limits. It would also be a good idea, if the instrumentation system permits, to mount a thermocouple into this transmitter-heat sink-cooling fan assembly to allow for real-time temperature monitoring. Figure 19 shows a radio frequency component-heat sink-muffin fan "sandwich."

Figure 19. RF component-heat sink-muffin fan "sandwich."

Other considerations that should be taken into account during the process of designing and procuring RF components for a research vehicle include test range-specific requirements for tracking and maintaining positive control of vehicle position relative to range boundaries. Generally speaking, for UAVs it is required to have redundant means of verifying the flight path of the vehicle within range boundaries, and should it violate those boundaries in an uncontrolled fashion, to be able to command either a positive arrestment or destruction of the vehicle. These requirements can and have been met in a variety of ways. For example, a vehicle may be equipped with two global positioning system (GPS) tracking systems, or one GPS system and the use of flight-test range radar. Radar systems usually require the vehicle to carry a matched transponder such that interrogations by the radar are met with a positive, identified response from the research vehicle; in this case, integrating this transponder will be part of the design considerations for the vehicle, including its integration with the other RF components. A secondary or redundant GPS system is less obtrusive because it is passive as opposed to the active RF operation of a radar transponder.

Care must be taken to avoid collateral interference from an on-board GPS with other RF systems of the aircraft, or other electronic devices which tend to radiate elevated levels of electromagnetic interference. Locating the GPS receiver away from other potential emitters is important unless the GPS device itself is well shielded against outside sources of interference. Antenna placement is also important; the GPS antenna should be placed as far as is practical from transmitter antenna. This arrangement is especially important if the RF band being used by the other components is L-band, because this band lies very near the GPS frequencies. Harmonics and sidelobes from L-band emitters, particularly wideband emitters carrying video signals, can easily swamp the relatively low-level GPS signals. If operating in L-band is unavoidable, and interference with GPS signals is detected, high-quality RF bandpass filters are available specifically for this purpose and will usually resolve the problem.

- Selection of radio-frequency components should be done with the future flight-test site in mind as well as tracking and maintaining positive control of vehicle position relative to range boundaries.
- Frequency agility in our contemporary crowded spectrum environment is critical to productivity; frequency selection that can be performed in real time will be the most expedient.
- Careful consideration should be given to heat rejection, especially on heat-generating devices, such as transmitters.
- GPS signals are weak; give additional care to potential interference problems and antenna placement.

Ground Support Equipment

Although often left as an afterthought, ground support equipment will be required to support and service the research aircraft before, during, and after a flight. At a very minimum, provision should be made for the ground power necessary to keep the aircraft batteries fully charged during ground preflight operations. Depending on the duration and type of ground operations, and the ambient temperature, onboard electronic components may require some type of external forced cooling, even if simply a blower to keep air moving through the avionics compartments. If the heat load is high enough, chilled air may be required.

Typical ground support equipment for the 500-lb range class of subscale research vehicles has typically been a gasoline-powered generator (to supply AC power), a power supply to convert this AC power into regulated DC aircraft power, and either a blower or portable air conditioner, or both, to supply cooling air. These components can then be palletized and carried in the bed of a small pickup truck, for example, which in turn can also serve as the tow vehicle for the aircraft. An example of this arrangement, which provided excellent service for the X-56A MUTT project, is shown in figure 20.

Figure 20. The Polaris® (Polaris, Inc.) (Medina, Minnesota) tow vehicle and ground support equipment for the X-56A MUTT.

Vehicle-specific equipment other than the tow vehicle and the trailer might be needed to carry out any preflight procedures or checks, as applicable to the system design. Examples are the test equipment needed to verify the proper functioning of the flight termination system or monitoring of the engines during start and runup, or other electronic or mechanical devices specific to the aircraft. Figure 21 shows the ground support equipment connections to the X-56A MUTT during preflight operations.

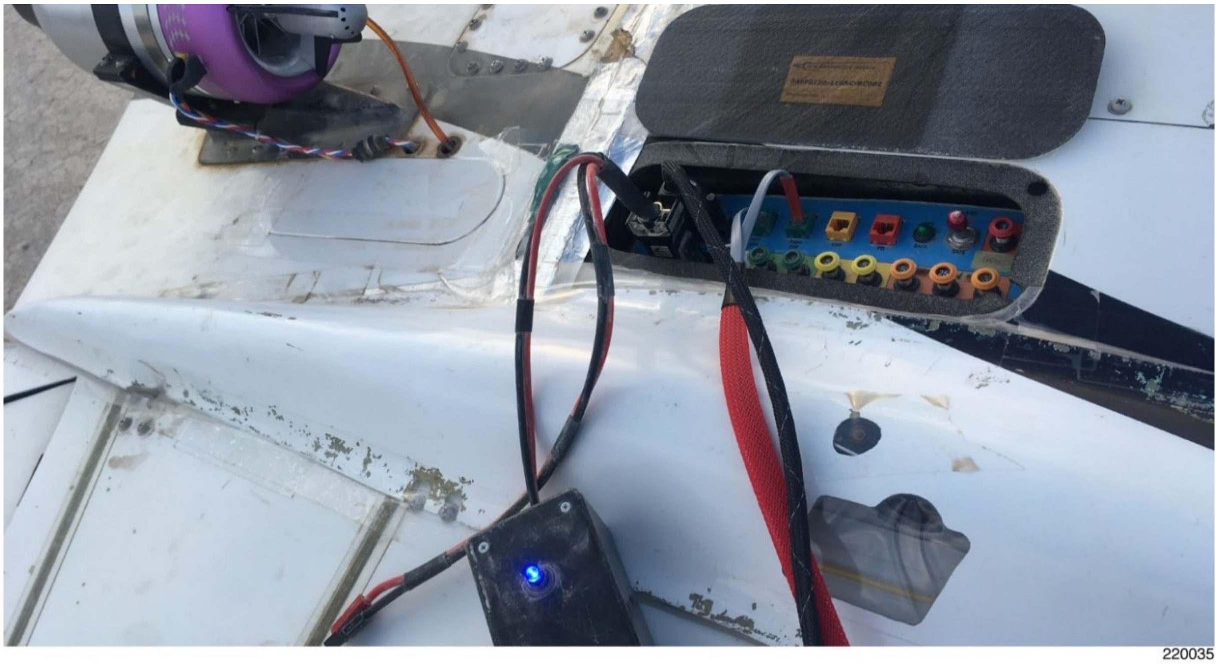


Figure 21. Ground support equipment connections to the X-56A MUTT during preflight operations.

- Ground support equipment should not be treated as an afterthought; equipment needs and connections should be predetermined.
- Electrical power, cooling, transportation, and radio (voice) communications will likely be required.

Flight Termination Systems

For the class of aircraft treated by this report (vehicles in the 500-lb range), both in terms of weight and size and also the “newness” of a research aircraft, for most flight-test ranges some type of flight termination system is likely to be required. Flight termination is a complex subject that is driven significantly by local range requirements and the philosophies of the prospective flight-test site personnel. For these reasons, some overall guidelines and “words of wisdom” based on the author’s over 20 years of experience with flight termination systems is presented here. Beyond this advice, it is critical to seek very early in the design process the guidance and requirements of the prospective flight-test host. If possible, also consult other similar programs that may have flown at the same site for their advice and experiences, as they will provide a “user’s” interpretation of the flight-test host’s rules and requirements for operating at the host site.

In the most basic terms, vehicles of this size, weight, and performance class will require a method to reassure the flight-test site host that the vehicle, under the worst of conditions, cannot leave the designated range boundaries and pose a threat to the public or infrastructure. The basic safety requirement for a worst-case scenario is that the range safety officers have a positive and reliable means of cutting vehicle thrust and lift, thereby effectively arresting the flight path of the vehicle and bringing it to the ground in as predictable a manner as possible. How exactly this termination will be accomplished is the engineering task of the vehicle engineers.

Removing thrust in powered vehicles is as simple as shutting down the engines. Engine shutdown can be accomplished in several ways, but generally the design options are limited. Examples of engine shutdown methods include closing a fuel valve, depriving the engine fuel pump of power, shorting out a spark ignition system, or shutting off all electrical power to the engine systems completely.

The second flight termination requirement is more difficult to implement, namely, to arrest the flight path of the vehicle abruptly and positively, and bring the vehicle to the ground in as predictable a manner as possible. Several design options exist for this requirement. Examples are parachute systems, spin parachutes, hard-over control surfaces, or explosive bolts that will break the vehicle into two or more pieces. In the case of inadvertent activation, the flight path arresting system often proves to be the most dangerous system, posing both safety and damage risks to personnel working on the aircraft and to the aircraft itself, respectively.

Guidance as to the nature of the design of a flight termination system is difficult to provide except by providing examples. The unique characteristics of each research aircraft and of each flight path arresting system make generalizations very difficult. Sometimes it might be obvious that a parachute deployment system would be the best approach, while in other circumstances it may be seen to be best to command the flight control surfaces to a hard-over position upon receiving the flight termination command. Whichever method or approach is pursued, it is critical that the reliability of the method be demonstrable to the range host to their satisfaction.

Again, if the flight-test site is known early in the vehicle design, the best approach is to engage the range safety authorities very early in order to obtain the relevant flight termination requirements and guidance. These termination systems are held to a higher, more rigorous standard than are other aircraft systems, and the required reliability can often be difficult to demonstrate. Further, the reasons for needing to activate flight termination systems arise when other aircraft systems fail, and it must be shown that the failure of these other research aircraft systems cannot impact the functionality of the flight termination system. This process quickly can become a circular train of logic. Even something as seemingly direct and positive as the detonation of explosive bolts can require rigorous lot testing and environmental testing to establish that the flight termination action of these devices is assured to the appropriate standards of range safety. The flight-test site authorities generally are most willing to help a new project meet these requirements to the satisfaction of everyone involved. This process does, however, usually take considerable time.

If the location of flight-test site is unknown during the design period of the research vehicle, and if a flight termination system is designed and implemented without this information, problems can follow upon arrival at the flight-test location. At this late point in the process, any shortcomings identified can be very difficult to remedy; therefore, schedule margin should be incorporated.

- Engage early and often with the flight-test site range personnel to obtain the relevant flight termination requirements and guidance; add schedule margin to address flight termination system requirements that are not able to be determined prior to test readiness.
- Whatever method of arresting the flight path is chosen, high levels of reliability of those methods will need to be demonstrated.

Recovery Systems

The X-36 Tailless Fighter Agility Research Aircraft, X-48B and C Hybrid or Blended Wing Body aircraft, and X-56A MUTT research aircraft each had a combined FTS and recovery system. The recovery system, so named because it was the designer's intention that this system would be deployed in the event of a catastrophic aircraft system failure or an unrecoverable departure from controlled flight. The intent was that in this event, a recovery system, typically a parachute system, could be deployed that would save the vehicle to some degree. Coincidently, this recovery system deployment would also effectively and abruptly arrest the flight trajectory of the vehicle, therefore simultaneously providing the functionality of an FTS. This synergy seems perfect and indeed often has been exploited to effectively combine these two functions into one system, however, they are nevertheless distinct systems with distinct levels of acceptable reliability in the eyes of those concerned with range safety. A recovery system can be accepted as being reliable enough by the aircraft designers and those sponsoring the research project; the FTS will be subject to the scrutiny of those concerned with range safety and the likely much more stringent standards imposed by that community. It is possible to "marry" the two systems and two sets of reliability standards, and indeed this operation has been done, but it should be considered early in the design process and noted that this desired outcome is not a given by any means.

The X-36 Tailless Fighter Agility Research Aircraft, X-48B and C Hybrid or Blended Wing Body aircraft, and the X-56A MUTT were equipped with recovery systems, as mentioned. In the case of the X-56A MUTT, the system was a commercial, Federal Aviation Administration certified recovery system originally designed and intended for the general aviation market for home-built, 2- and 4-place personal aircraft. In the cases of the X-36 Tailless Fighter Agility Research Aircraft and the X-48 BWB, the recovery systems were custom-designed for the aircraft, and in the case of the X-48 BWB, the system was quite elaborate, including impact-cushioning air bags which would inflate while the aircraft was under parachute descent. This degree of complexity was achieved at a substantial cost in terms of engineering design hours, fabrication and outsourcing of custom parachute components, and ultimately in the amount of weight carried by the research aircraft. This weight and volume penalty is carried by the aircraft on every flight, but the recovery system is used only in the direst emergency situation. This weight and volume could have been used for more fuel capacity, which would have allowed more test points to be accomplished on each flight.

Whether or not a recovery system will be carried on a research aircraft is a critical decision best made very early in the design process. The nature of the research and cost of the aircraft are of course important factors. For example, the purpose of the X-56A MUTT was to explore control methods of suppressing flutter. The nature of this mission inherently meant that the aircraft would be at great risk every time it flew into the flutter speed regime. The X-48 BWB was an experiment into the aerodynamic characteristics of its very unusual shape. Before its extremely successful flight-test program, the low-speed, high-lift characteristics of this shape were largely unknown, so again the risk of losing the aircraft early in the test program due to aerodynamic stall or unrecoverable departure from controlled flight was thought to be moderately high; therefore, a great deal of effort went into the design and incorporation of a recovery system.

Interestingly, only the X-36 Tailless Fighter Agility Research Aircraft recovery system was tested. A dummy body of similar weight and size was fabricated and incorporated into the recovery system components in as close to a configuration as possible to the real aircraft installation. This host body was then dropped out the back of a C-130 military transport aircraft (Lockheed Martin) (Bethesda, Maryland) and the recovery system initiated at the same altitude as it would be activated in an actual aircraft emergency. The recovery system worked perfectly; the terminal impact velocity was measured to be extremely close to the analytical predictions.

For the other two aircraft, only limited testing of the system was performed – basically, component level testing. The X-48B and C Hybrid or Blended Wing Body aircraft drogue parachute system was actually qualified to FTS reliability standards, and this qualification was performed by repeated firings and deployments of the parachute. This testing was possible because the deployment of the drogue parachute was performed pneumatically and was non-destructive in nature. Repeated firings only required that the parachute be refolded and repacked into the launch tube. The other elements of the recovery system were not tested, save for in-hangar inflation of the air bags.

Without representative testing, the likelihood of a recovery system functioning as intended and actually being able to "save" the research vehicle is difficult to quantify. Testing that would quantify that probability is very expensive, so often the recovery system is designed and installed but never tested. There are philosophical arguments that can be made on all sides of this topic; my opinion is that given a clean-sheet-of-paper design, I would forego any efforts toward a recovery system and rather give maximum consideration to making the aircraft as reliable as possible within given cost constraints.

Given the nature, purpose, and size of the vehicles discussed in this report, going beyond a "single-string" system in terms of backup systems and thus reliability is quite challenging. Still, given modern electronics miniaturization, there are at least some options available to provide additional "robustness" to individual system failures, or at least those deemed the most catastrophic. For example, solid-state microelectromechanical system-type rate gyros are robust and inexpensive, as well as being small. Rather than take up vehicle volume with a recovery parachute, why not fill that space with a second, redundant set of rate gyros? The X-56A MUTT centerbody volume was extremely limited, but the same volume that nearly all of the flight electronics volume occupied was taken up by the recovery parachute. Without the parachute, it would have been possible to double the avionics volume for additional redundant systems or add significant fuel volume.

The message is that careful consideration should be given to the perceived benefits and tradeoffs of equipping a research aircraft with a recovery system. Consider how much it will cost, how much volume of the aircraft it will occupy, whether there is sufficient project funding to actually test the system, and how the volume required for the recovery system could perhaps be better utilized. Certainly, some research missions put the aircraft itself a great risk, and in this situation, the equation for the necessity of a recovery system balances differently. It is not a simple tradeoff; but neither should a new project fall into the trap of believing that a recovery system will be the answer for all risk to the aircraft.

- Vehicle recovery systems and flight termination systems are two different things; however, it is often possible to find adequate synergy between the two to allow for a common system.
- Consider very carefully whether a recovery system is warranted and justified; these systems involve significant design and implementation and testing costs and carry permanent weight penalties.
- Building in quality and some degree of reliability into the aircraft systems may pay much greater dividends in the long run as opposed to an expensive and not-expected-to-be-used recovery system.

Flight-Test Durations

In this section the author shares some memorable flight-testing experiences accumulated over his more than 20 years and several projects' worth of experience. One consistent theme has been that the estimated duration of a given flight-test campaign, as communicated from the initial project formulation, has been woefully shy of what was the actual duration. There are several reasons for this discrepancy; this section will explore a few.

As one arrives at the flight-test site, the first change of schedule is inevitably due to the fact that the research aircraft completed fabrication prematurely. The funding source is often different for flight testing than for design and fabrication. Financial and performance metrics pressures can thus build up, "motivating" the aircraft fabrication personnel to complete the fabrication as best as possible, and prepare the aircraft as quickly as possible for shipment to the flight-test site. Some level of integration testing may be performed at the fabrication site; this testing is helpful in reducing risk and costs at the flight-test site as long as the tests are not cursory in nature and shipment to the flight-test site occurs with positive outcome of the tests. Otherwise, a significant portion of "travelled" work may be transferred from the manufacturing site to the flight-test site, becoming part of what is then called "flight-test phase activities." This "travelled" work frequently can last from several weeks to several months, resulting in an extension of the time-duration.

Understandably, many integration-level tests cannot adequately be performed anywhere but at the flight-test site; for example, RF integration testing of the telemetry and command and control links, high-power engine runs, and tow- and taxi-testing. These tests require the integrated systems of both the research aircraft system, ground control facilities, and frequently the fixed infrastructure (antennae) of the flight-test site. Time spent performing these types of testing is time well spent and should be expected and budgeted for in the flight-test project plan. Testing that could have been accomplished at the fabrication site, however, or, more significantly, testing that could have been more appropriately and more efficiently performed there, are examples of "travelled" work that substantially lengthens the duration of the flight-test phase of the project. "Travelled" work also can increase costs if specialized personnel skill sets must travel to the flight-test site.

Again, often, "travelled" work is unavoidable, but such work should be carefully considered and monitored, and perhaps used as justification to proportionally adjust the size of the flight-test budget. If programmatic margins (both time and dollars) are strained due to increased duration of the flight-test phase, this schedule and cost pressure usually peaks at or slightly after the actual business of research flight-test begins. This state can lead to a hurried approach, increased risk tolerance, and non-conservative decisions, which in turn can lead to a crash or other flight-test incident that might have been avoided given more "breathing room," improved risk mitigation, and time to think.

- Schedule and funding estimates during design and fabrication should be robust to avoid "travelled work" moving into the flight-test phase.
- Appropriate re-scoping of the flight-test phase may be needed to accommodate "travelled work" and avoid necessary schedule pressure on the test-team.

- Decision authority of the flight-test team should be pre-determined and clearly communicated to the test team; test productivity can be improved with greater decision authority granted.

Weather Considerations

The first section of this report discusses many of the most significant lessons in terms of vehicle design considerations; these lessons are so very significant because those design decisions, be they good or bad, end up staying with both the vehicle and the flight-test effort for the entire duration of the effort. It is best to avoid potential problems by designing them out, rather than either correcting them later or living with them in resignation.

Other lessons take the form of numerous other factors affecting the flight-test process - in particular, those factor that can be neither well-predicted nor controlled. Foremost among these factors is, of course, the weather. The vehicles discussed herein all share a very limited ability to cope with adverse weather conditions, be they clouds, turbulence, precipitation, excessive heat or cold, or, most notoriously, winds. These vehicles have restrictive flight envelopes, particularly in terms of winds in magnitude, gusts, and direction. Depending on the chosen flight-test site, historical weather patterns and seasonal variations should be considered when formulating and funding the flight-test plan, especially one of the “limited duration” variety: those planned to last only a few weeks or months. This limited schedule may be executable if the targeted test period falls within the appropriate season with regard to historical weather patterns. For example, planning the flight testing of a wind-sensitive aircraft in the early spring (a typically very windy season) at Edwards Air Force Base (Edwards, California) is likely to lead to a disappointing outcome. Planning the same flight-test regime for the late autumn (a season of low or no winds) will substantially increase the chances of execution and success.

Sometimes surface winds affecting landing and takeoff limits are favorable, but turbulence aloft and wind-shear variations with altitude may be either endangering to the aircraft or might mire the data beyond usefulness. This wind condition might be difficult to ascertain before committing to flight, unless perhaps a surrogate vehicle can be launched during preflight activities to assess the turbulence and other conditions aloft. This approach was used with great success with the X-56A MUTT flight research effort. Even without a dedicated surrogate, pilot reports from other aviation activities might be available to help with the assessment of conditions aloft.

Depending on actual weather sensitivity, flight-test cadence can vary widely. Many projects over the years have planned one or two test flights per week. Again, the seasonal weather patterns of the flight-test site need to be considered; the “two per week” plan can fall apart quickly, leading to longer-than-expected flight-test programs.

- Historical weather trends can provide “best guesses” of target flight windows as well as guidance for necessary schedule margin to accomplish all planned flight sorties.
- Surrogate vehicles during preflight may provide valuable in determining wind conditions aloft prior to engaging in subscale flight test.

Conclusions

This report presents some experiences and recommendations gathered over 20-plus years of being intimately involved with the design, development, and flight testing of unmanned subscale research aircraft within the size range of 350- to 1500-lb gross takeoff weight. The majority of the recommendations take the form of design considerations: features and design choices to consider when beginning a new design. Most of the considerations have been formulated by observation of shortcomings in the design of aircraft; many recommended courses of action are reasonably simple to take by incorporation into new designs but would be difficult to retrofit on existing aircraft. Providing sufficient fuel volume for efficient flight testing is an example.

Limitations that exist regarding how well this size class of research aircraft can serve as a means to explore new aerospace research topics. Dynamic scaling and Reynolds number effects, the lack of transonic or supersonic flight regime capability, brief flight durations, and limited volumetric capacity all constrict the scope of aerospace-relevant research that can be conducted; however, the price point at this scale has consistently shown an appeal to both the Government and private industry as a palatable cost and reward tradeoff when examining available options to take a concept to flight. Considering the recommendations and considerations provided in this report will, hopefully, increase its utility and the likelihood of achieving the stated research goals.

At a minimum, many of the design considerations shared herein will make the aircraft much more maintainable and “user friendly” and provide for efficiencies to be realized once the flight-test phase of the project begins, particularly if that phase runs far longer than originally expected.