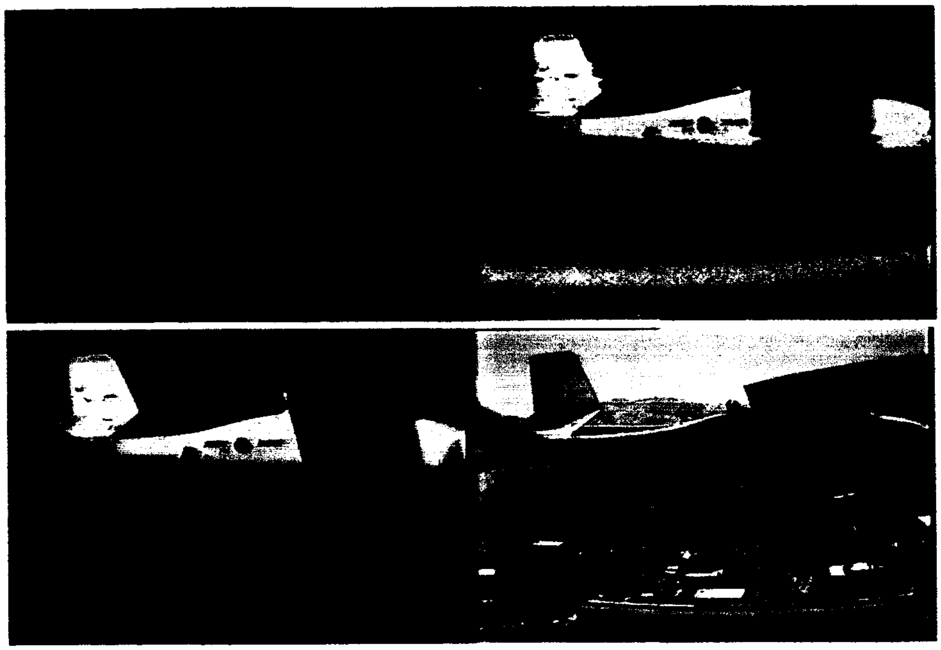
Design, Development and Testing of Airplanes for Mars Exploration



Final Report
on
a series of grant tasks
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by

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Introduction

The opportunity for a piggyback mission to Mars aboard an *Ariane* 5 rocket in the early spring of 1999 set off feverish design activity at several NASA centers. This report describes the contract work done by faculty, students, and consultants at the California Polytechnic State University in San Luis Obispo California (Cal Poly/SLO) to support the NASA/Ames design, construction and test efforts to develop a simple and robust Mars Flyer configuration capable of performing a practical science mission on Mars.

The first sections will address the conceptual design of a workable Mars Flyer configuration which started in the spring and summer of 1999. Following sections will focus on construction and flight test of two full-scale vehicles. The final section will reflect on the overall effort and make recommendations for future work.

Configuration Development

These airplanes were based on the original 1999 airplane designed to fit the noncircular "breadloaf" aeroshell for the proposed 2003 ASAP launch on an *Ariane* 5 as a secondary payload. The breadloaf aeroshell is shown in Figures 1 and 2. The geometric constraints of the launch platform meant that the spacecraft had to fit into the annular area between the outer payload shroud and inner *Ariane* 5 primary payload support structure. In practice, this meant the interplanetary bus spacecraft had to occupy 90 degrees of a circular arc. The largest conventional circular aeroshell which would fit onto the quarter circular bus planform was only 31.5 in (80 cm) diameter, which meant that it would be able carry a very small aircraft as its payload.

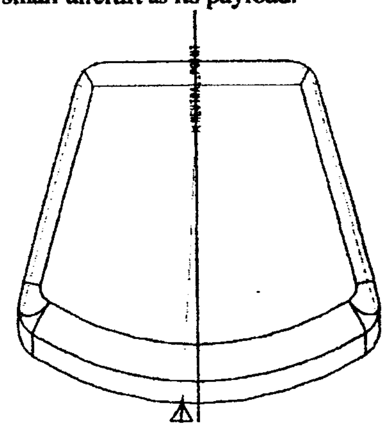


Figure 1. The Noncircular Breadloaf Aeroshell was Developed and Tested in Small Scale at NASA/Ames in 1999.

The "rounded rectangular" or "breadloaf" aeroshell was an attempt to greatly increase the volume available for the airplane. This aircraft originated as a design exercise which was started at the Naval Research Laboratory (NRL) to see just how well an airplane could be fitted into a breadloaf shape, and from that to determine if there was enough performance improvement to justify the development effort which would be required for the new aeroshell.

The NRL configuration supplied to Ames at 5:30 PM on Thursday, April 29, 1999 is shown in Figure 2 which also shows additional details of the breadloaf aeroshell.

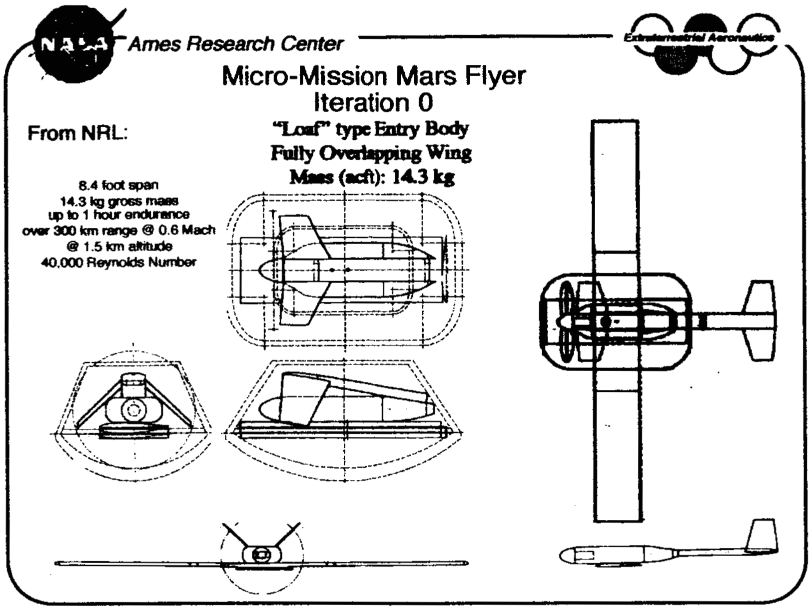


Figure 2. NRL Supplied a Small Mars Flyer Configuration Based On Their Earlier Work.

The configuration supplied by NRL had sufficient tail volume for flight at low altitudes on earth, but that would not be adequate for flight at either high altitudes on earth or on Mars. The first iteration, then, focused on providing more horizontal and vertical tail volume to meet these conditions. The Iteration 1 configuration was also resized for a Mars science mission which grew its wing area slightly and increased fuselage width.

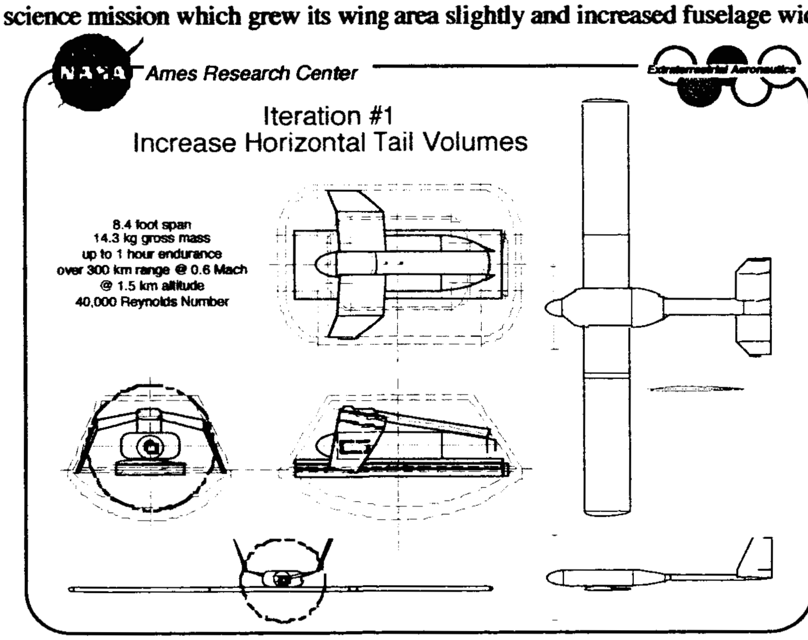


Figure 3. The First Iteration Added Stability and Payloads as Design Considerations.

Iteration 2 added further fuselage volume for payload, motor, and fuel as internal systems were fleshed out. At this point, approximately twenty-four hours into the design cycle, a subsonic minimum induced loss propeller was designed and added, as shown in Figure 4. Note the upper aft fuselage notch to accommodate the folding tail boom. Also note throughout these configuration iterations all the unused space beneath the wings in the aeroshell.

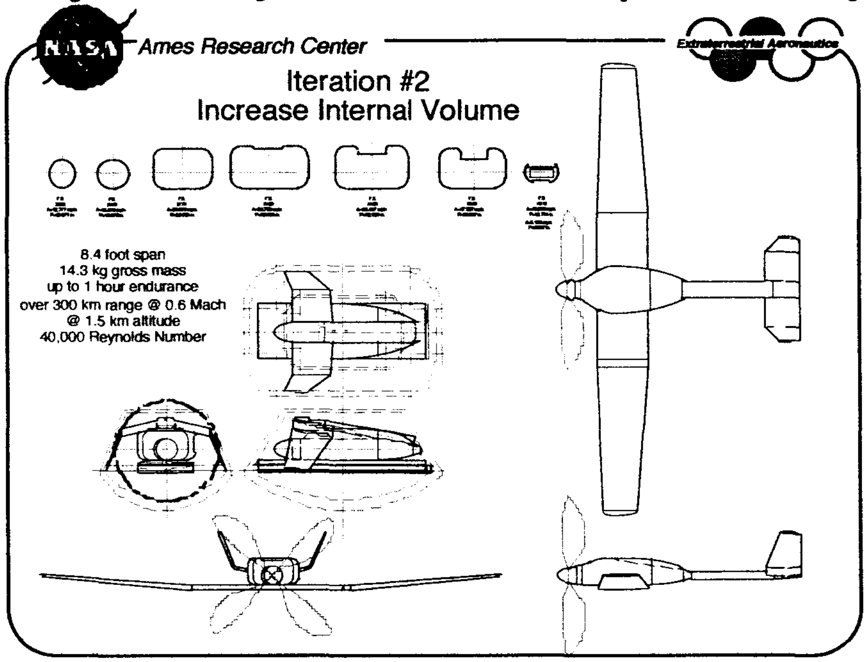


Figure 4. The Second Iteration Provided More Internal Volume and a First Cut at a Propeller.

By iteration 5, which was finished around 10 PM on Saturday, May 1st, the final shape was close. Note in Figures 5 and 6 the packing efficiency of this configuration—there is more space available in the fuselage for payload and propulsion and the airframe fits more snugly into the aeroshell. Note in Figure 6 in particular the asymmetry of the left and right wing outer panels, which was done to allow them to nest with one another when in the folded position. Note also the large diameter two-blade subsonic paddle-bladed propeller which is a significant simplification of the four-blade minimum induced loss design initially created for this configuration. Aside from ease of manufacture, the simpler prop also folded more easily against fuselage sides while providing comparable efficiency.

By Sunday morning, May 2nd, the small but capable design team had a workable configuration which was both innovative and practical, and perhaps elegant. One of the team members (Parks) began building a full-scale unfoldable mockup of the Mars Flyer configuration which was given the designation NASA-726 on Monday, May 3rd, 1999, several views of which are shown in Figure 7. A second team member (Youngren) began CFD runs of the wing/fuselage intersection fairing to determine what additional design work had to be done to alleviate bad aerodynamic interference effects at the very low Reynolds Numbers and high subsonic Mach Numbers expected over the Martian surface. The third team member (Hall) prepared a large-scale drawing of the baseline configuration to check payload and propulsion system fit as well as checking mission performance, and preparing briefing charts.

The three person team that created this mockup presented it to NASA/Ames Codes A and S, Boeing Phantom Works staff, and NRL staff at 8:30 AM on Tuesday, May 4, 1999—four and one-half days after starting the design cycle.

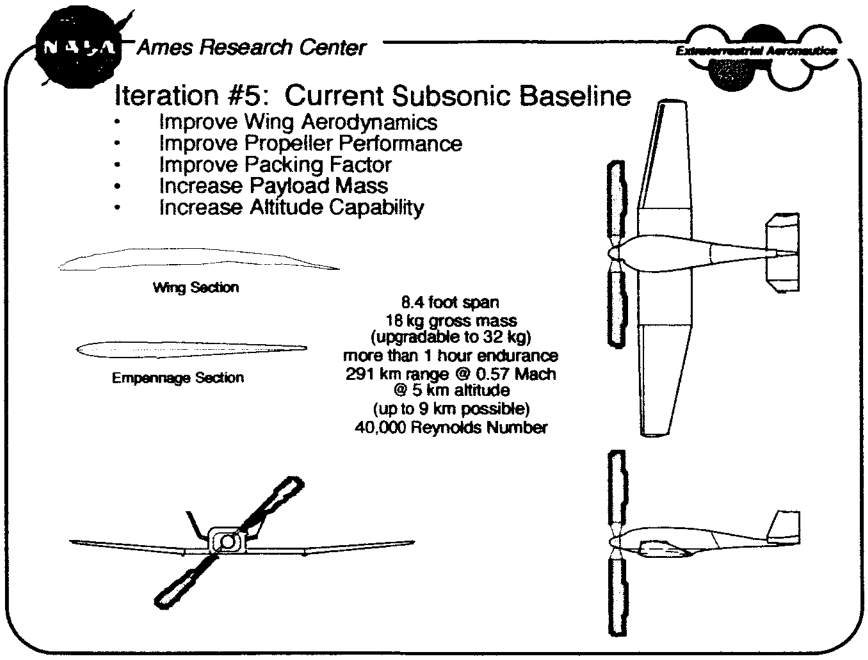


Figure 5. Iteration 5 was the Final Mars Flyer Configuration from This Design Cycle.

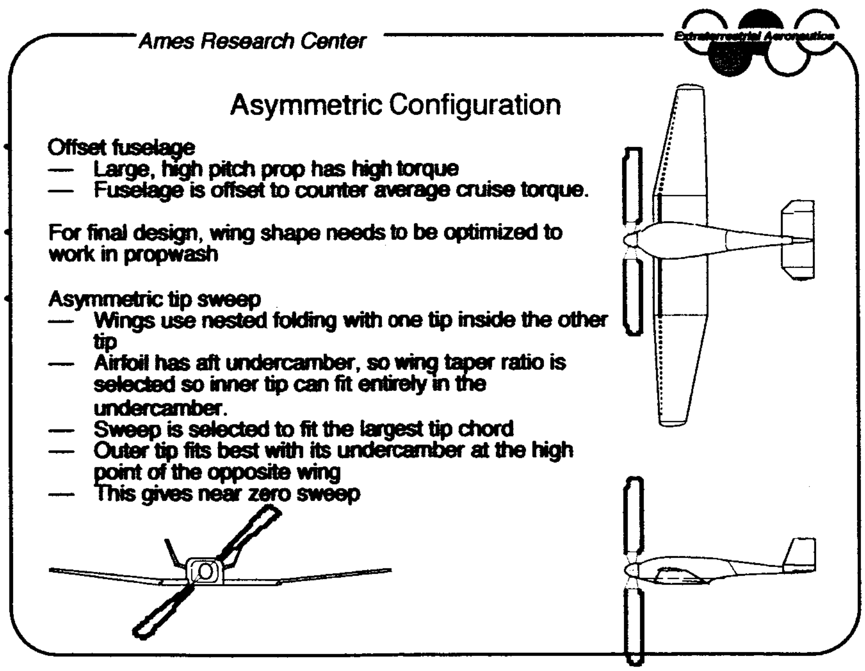


Figure 6. Iteration 5 Became the Baseline Mars Flyer Configuration.

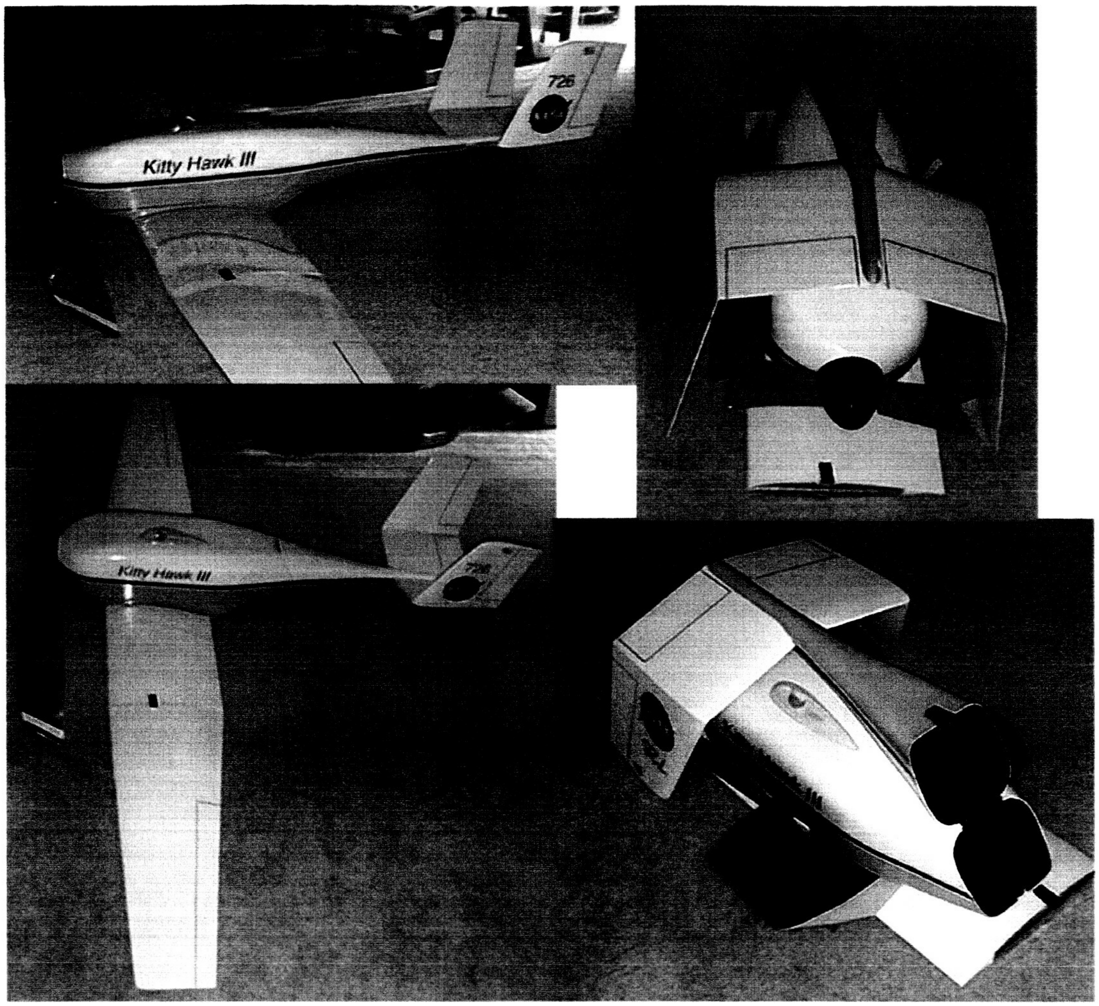


Figure 7. This Full-Scale Mockup of the Mars Flyer (NASA-726) Shows Its Deployment Scheme.

As the competition for the ASAP launch continued, it became obvious that a flight test of the aircraft configuration would give NASA/Ames a competitive advantage. That decision led to the flight test program which will be described here. Preceding the flight tests, though, was another round of design iterations to take care of aerodynamic problems that would lessen flight test risk. The first area examined was the wing root/fuselage fillet which is shown in Figure 8. Two approaches were taken. The first was to redesign the forward fuselage to minimize aerodynamic interference and Figures 9a & b show this approach. The more practical fix, however, was to reposition the wing on top of the fuselage. A high wing position would complicate stowage in the breadloaf aeroshell but would solve the fuselage/wing junction interference problem which showed up in early CFD runs. Given time and budget constraints this departure was justified to assure that both low altitude and high altitude flight tests could be quickly conducted. The addition of a low speed terrestrial flight test series to the original design requirements made necessary the addition of a larger span horizontal tail, as shown in Figure 9b. Later analysis work based on early flight tests confirmed that the larger tail area may be necessary for flight on Mars.

The second team member (Youngren) began a series of computational fluid dynamic (CFD) runs using industrial strength codes. Results showed that the flow field around the low-wing/wing root/fuselage junction was complex enough at Martian flight conditions that shifting to a high wing configuration may be a preferable solution to continuing development of the low wing configuration. Results of two sets of CFD runs are presented in Figure 10.

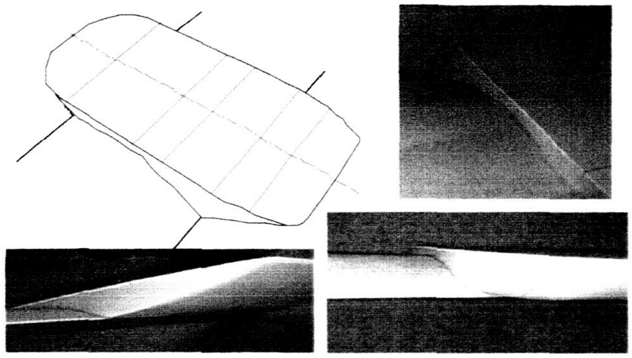


Figure 8. The Baseline Wing Root/Fuselage Junction Presented an Aerodynamic Challenge.

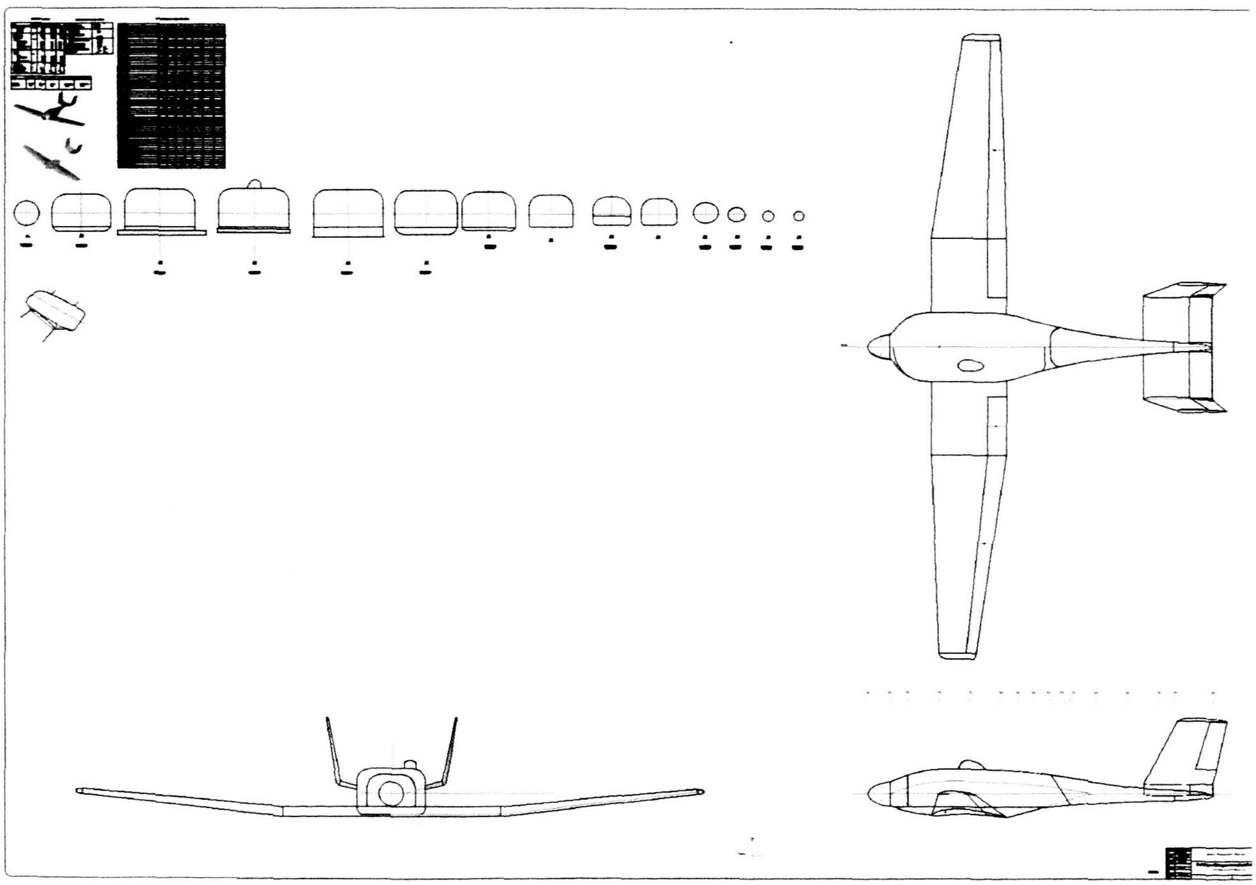


Figure 9a. The Baseline Mars Flyer Configuration Required Detailed Aerodynamic Development Work in Several Areas Before It Could Be Used as a Terrestrial Flight Test Article.

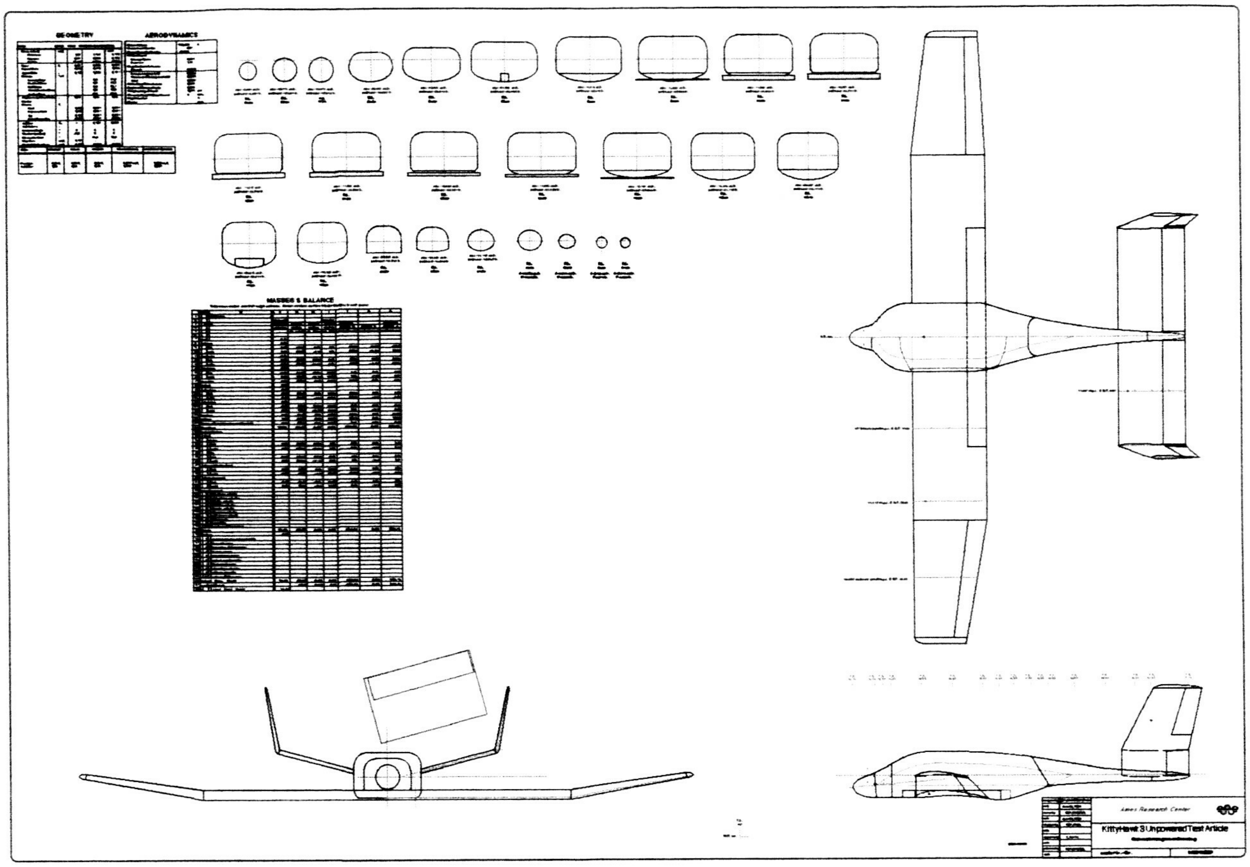
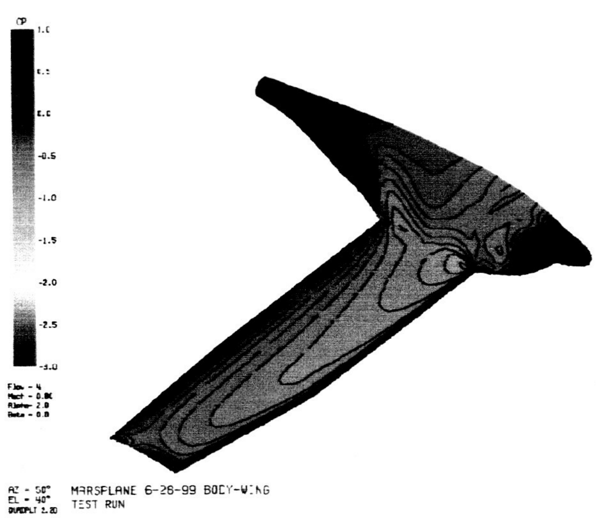
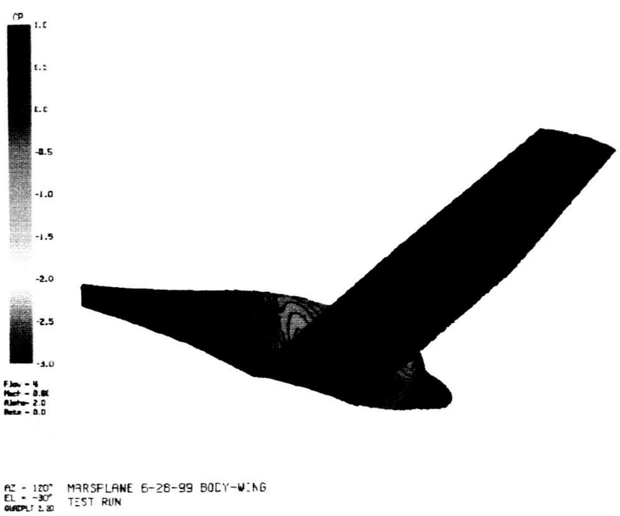


Figure 9b. One Attempted Fix to the Wing Root/Fuselage Junction was a Lower Fuselage Redesign.





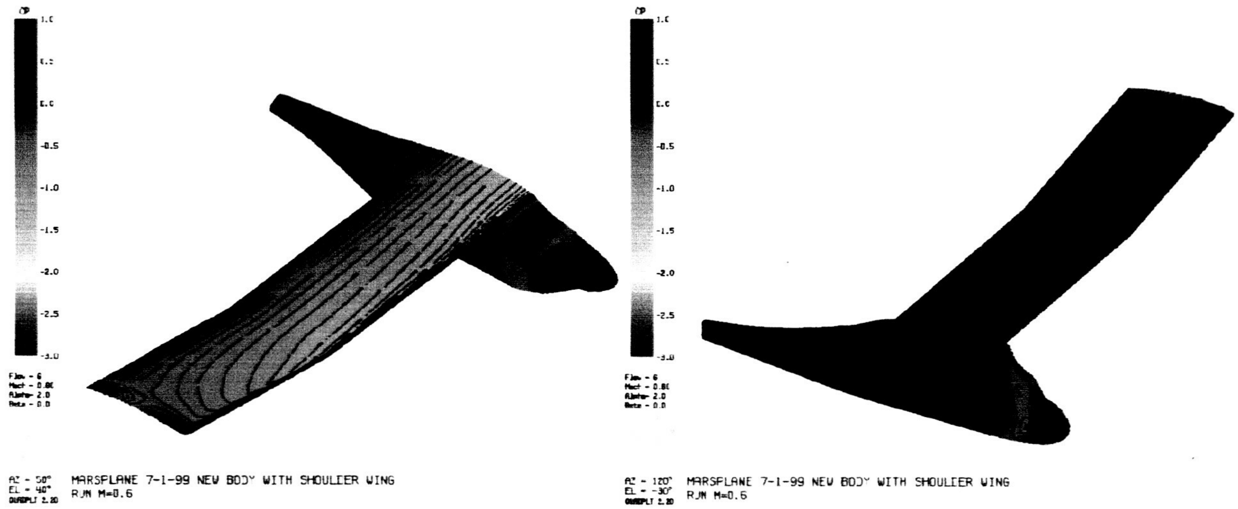


Figure 10. MSES CFD Runs Confirmed the Top of the Fuselage as the Preferred Wing Location.

These configuration fixes for terrestrial flight tests were fabricated into the full-scale unpowered test article, NASA-729, which is shown in Figure 11. Tests with it and its successors will be addressed in more detail in the next section. Note the small span horizontal tail.

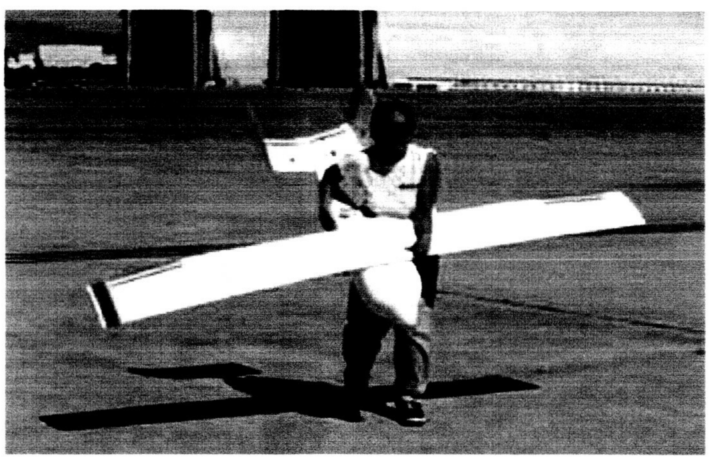


Figure 11. The Revised Configuration (NASA-729) Shows No Change Other Than Wing Position and Outer Panel Dihedral from NASA-726.

Flight Tests

The original goals of the flight test series were to verify the aerodynamic feasibility and handling of NASA-729, and then to perform several high altitude tests which would more closely replicate flight conditions on Mars in order to see how the basic configuration behaved. The high altitude tests had two main goals: first to verify performance at realistic combinations of Mach and Reynolds Numbers (there is a very limited aerodynamic database under these conditions), and second to verify that it is possible to do a pullout from a tail up position into level flight in Martian conditions. This second goal reflected the intended initial launch conditions at Mars.

The goal was to demonstrate Mars relevant performance, but the reality was that the flight tests were conducted on Earth. The low altitude tests would replicate flight at Martian Reynolds Numbers but flight speeds would be closer to a brisk walk than to those planned for the actual Mars mission. Since the eventual Mars Flyer would be allowed to crash at the end of its mission, no considerations would be made on it for landing. The Earth-based flight test airplanes, however, would need to make many flights each, so landing with minimal damage was critical. While some type of retractable landing gear might have been possible, it would have created a development effort beyond available funding and time.

The asymmetric tapered planform of the Mars configuration of Figure 9a was totally driven by space efficient wing folding to fit as much airplane as possible into the breadloaf aeroshell. Since the terrestrial test airplanes would never have to fold, cost and schedule pressures led to simplifying the wing planform. The new wing was left-to-right symmetrical and had much larger tip chords than the earlier designs. This allowed CNC machining of just a single, constant chord panel with 5 foot span. The three wing panels could then be made from the same mold with wingtip taper created by trimming the wing trailing edge at an angle in the top view. The result was an airfoil with a very thick trailing edge outboard, but analysis showed that, due to the low Reynolds Numbers at test conditions, there wasn't a significant drag penalty. The under cambered airfoil also provided useful washout to minimize chances of tip stall. Since the initial flight tests would be unpowered, there was no need to mount the fuselage asymmetrically on the wing, as on the original configuration, to counteract torque from a very large, slow turning propeller.

This design was then finalized, tooled, and fabricated in the early fall of 1999, as NASA tail number 729. Refer to Figure 11 again for a photo of it. This aircraft was successfully flown approximately three dozen times at low altitude in the fall of 1999 at NASA/Ames Research Center. While the flight was not instrumented, NASA-729 qualitatively proved to have good handling, and quite good aerodynamic performance.

The ASAP mission had by the time of these flight tests been transferred to NASA/Langley, and shortly after that was canceled by NASA/HQ. Work at Ames experienced a brief funding hiatus. The NASA/Ames Mars Flyer flight test program resumed in 2000 when center funding became available. Testing this time wasn't tied to a particular mission, but was conducted to prove the feasibility of sustained flight in Martian atmospheric conditions and to prove the feasibility of a high subsonic speed, low atmospheric density pullout.

NASA-729 was reactivated for additional low altitude flights and a new airframe, NASA-731, was constructed for high altitude tests. NASA-731 was modified to reduce risk and development effort since it no longer had to be tailored for the ASAP mission and the breadloaf aeroshell. First, the tail was enlarged to that shown in Figure 9b. The NASA-729 tail size worked well at low altitude, but for high altitude, the NASA-729 airplane would need stability augmentation, particularly artificial damping in both pitch and yaw. This meant a significant effort in analysis, ground testing, and flight computer and software development. A simple alternative would be to enlarge the horizontal tail. The larger horizontal tail was a simple fix and saved both time and money. See Figure 12 for a drawing and photos of the NASA-731 configuration.

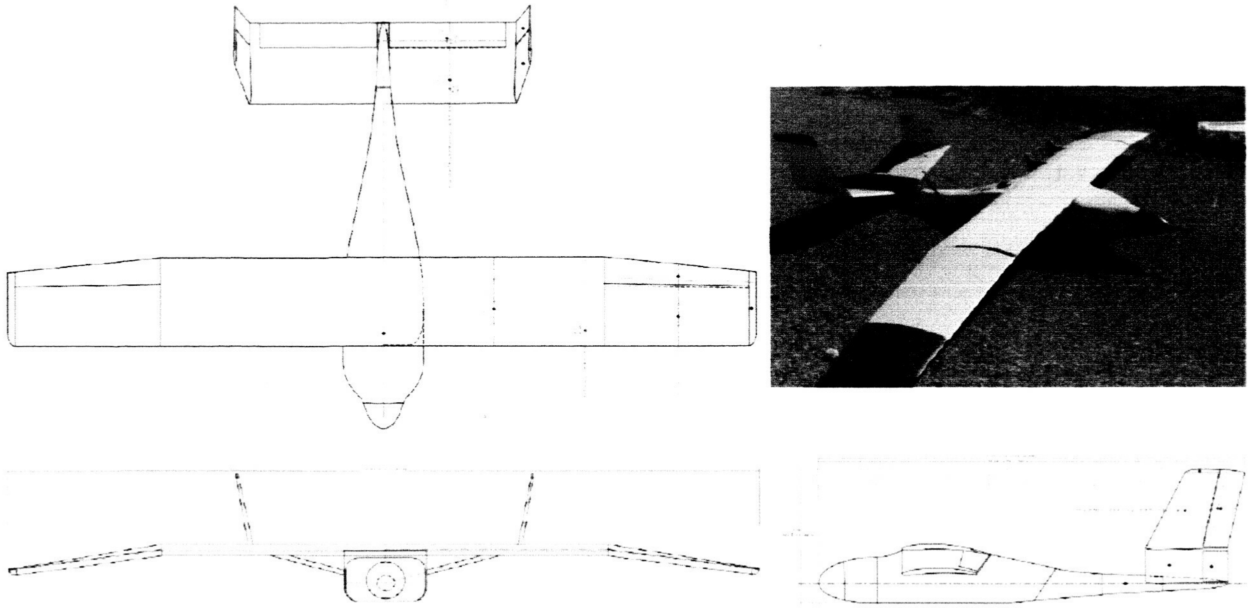


Figure 12. NASA-731 Incorporated Modifications to Facilitate an Unpowered High Altitude Test.

Once the tail size was selected, some analysis was done to determine the wing dihedral change needed to minimize the rolling moment due to sideslip. This essentially decouples the yaw and roll modes in the lateral dynamics, which makes flight software design easier and more robust. Because of the high wing and the increased dihedral effect of the enlarged horizontal tail, the outer wings ended up with slightly negative dihedral (anhedral). NASA-731 was successfully flight tested at both low and high altitudes in August 2001 at both NASA/Ames Research Center and at Tillamook Airport Oregon. The Tillamook flight began with a tail-high drop from a balloon floating at 103,200 feet and the aircraft achieved brief level flight at around 93,000 feet where the Figure 13 and title sheet camera frames were taken.

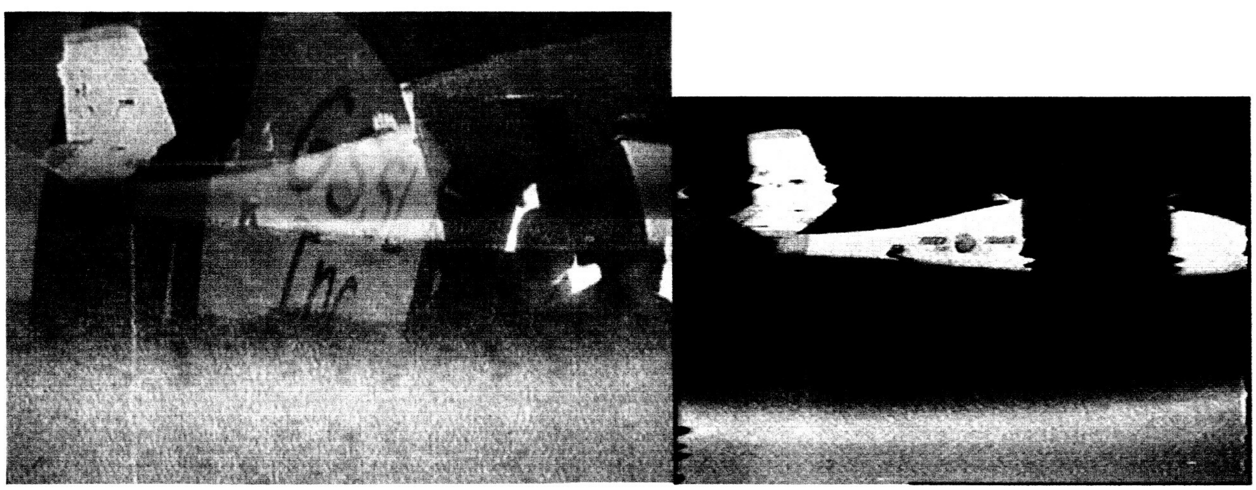


Figure 13. This Wingtip Photo Shows NASA-731 Flying Level on the Edge of Space.

The August 2001 tests showed the efficacy of the basic design but also pointed to some areas that could be improved; therefore, another flight was planned for later in the fall of 2001. The August flight showed that the pullout altitude loss was greater than predicted by a considerable margin due to a combination of conservatism in the autopilot commands and to a transonic pitch down trim change (the classic Mach tuck of the late 1940s). Work began on an improved version of NASA-731 that could operate at much higher altitude, with a goal of achieving level flight above 100,000 ft.

The first part of these modifications was a weight reduction program for all aircraft systems. In addition, the wingspan and area were increased by fabricating larger wingtip panels. Analysis showed that this airplane could work when dropped from 115,000 ft, and would achieve level flight at 104,000 ft. The nose was lengthened to allow more volume for avionics, motor, and propulsion batteries. These additions eliminated the need for the nose ballast carried in the first high altitude flight.

Due to the events of September 11, 2001, the next high altitude flight test was delayed, and as a result of the delay, the scope of the next flight test was substantially changed to measure the performance of a new propeller design specifically for use on Mars as well as to test the new configuration. See Figure 14 for the NASA-731A configuration shown with a temporary landing gear dolly attached for low altitude tests.

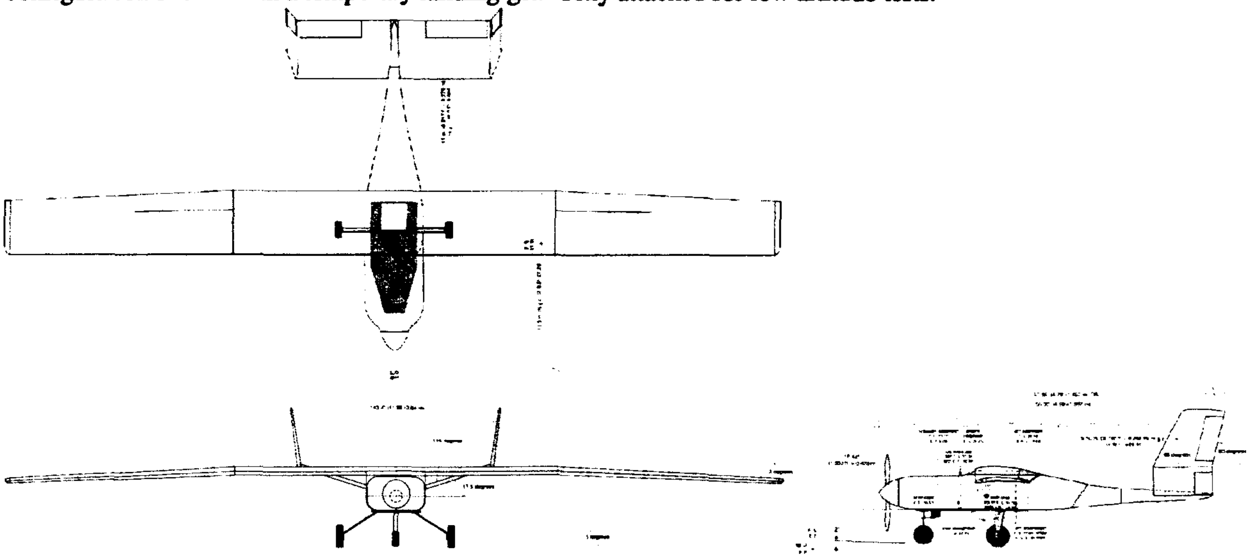


Figure 14. The Powered Configuration Became NASA-731A. Note the Lengthened Nose.

The motor and a low altitude R/C model propeller were installed in the nose (visible in Figure 14), all the systems were upgraded, and the aircraft was flown in this configuration at low altitude in early September, 2002 at Tillamook Oregon. The brief series of low altitude taxi and flight tests were followed by changing out the low altitude propeller for a supersonic high altitude unit and a high altitude drop from a balloon floating at 115,000 feet. This flight was unsuccessful and resulted in the loss of the aircraft.

Referring to Figure 7, note that the original configuration had a propeller designed to maintain a subsonic tip speed. This was typical of high altitude propeller design at that time. The result, while it appeared to have an efficiency of over 70%, was a very large diameter with a commensurately slow rotation speed. This translated to the need to carry a large, heavy gearbox, and meant that the airframe would encounter very large torques at high power; hence, the fuselage was offset from the center of the wing by several inches to compensate.

Once the configuration was revised with the redesigned, lengthened nose and heavier internal equipment, Professor Mark Drela of MIT designed a new propeller. The earlier subsonic tip speed propeller could be made to work, but a supersonic tip speed propeller would have advantages of both smaller size and more closely matched propeller rotation speed to motor speed. If carefully matched, a speed reducing gearbox could be eliminated altogether, simplifying the power train and improving overall propulsion efficiency.

Professor Drela designed both the propeller blade shape and all the airfoils needed along their span. The result was a propeller that promised slightly better efficiency while reducing the diameter to about one-third of the subsonic design. The propeller required careful structural design, since the airfoils were very thin: 1% at the tip, 5% at the root. This was a result of maximum Reynolds Numbers of 35,000 at the root with the tips under 20,000, and Mach Numbers of up to 1.08 at the tip.

It was also critical that the propeller maintain the proper shape under flight loads. The thin airfoils only have a small range of angles-of-attack where they are aerodynamically efficient and their thinness results in blades with low torsional stiffness. Once the blade shape was finalized, their preliminary structural design was completed and the graphite laminates determined. A finite element analysis was performed to determine the amount of blade twist that would occur under flight loads. The shape of the propeller blade was adjusted so that flight loads would cause it to deform to the desired twist distribution. This geometry was then used to CNC machine aluminum molds for blade fabrication and two propeller sets were made. See Figure 15 for propeller details.

This is the configuration of NASA-731A that was launched on September 9, 2002 over Tillamook. The aircraft dropped from its carrier balloon and began a pullout that lasted approximately 41 seconds before flutter destroyed it at approximately 103,000 feet. At that time, the propeller was considerably over speed and tip Mach Numbers approached 1.8 when it flew apart.

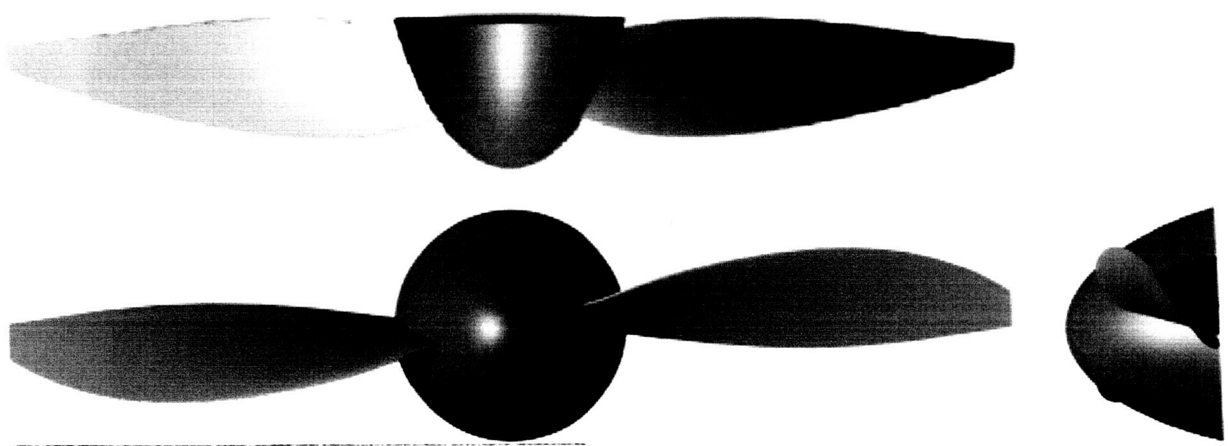


Figure 15. The Supersonic Propeller Would Provide Size Complexity Reduction Benefits While Matching Propeller Speed with Motor Speed.

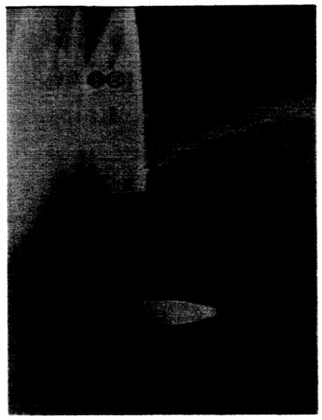


Figure 16. This Movie Frame was Shot While NASA-731A was in a Controlled Pullout.

Conclusion

The NASA-731A configuration evolved rapidly from a set of requirements that were obsolete by the time the airplane flew. Although it no longer represented a full-scale Mars science airplane, it had utilitarian use as a testbed to learn more about operating in Martian conditions—specifically, combinations of low Reynolds Number and high subsonic Mach Number—and of testing the deployment scheme envisioned from the NASA/Ames Discovery '96 Airplane for Mars Exploration proposal. Flight tests of the unpowered model, NASA-731, were successful and proved the efficacy of the basic design and the launch method. The powered version, NASA-731A, however, introduced uncertainty about both the launch approach and about the practical capability of propellers to produce significant thrust under Martian conditions. More will be said about these two configurations and their test flights in a companion report to be released later in 2004.