Sun-Powered Aircraft Designs

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Two piloted aircraft have been developed by AeroVironment Inc. and flown powered solely by photovoltaic cells. The 30.8-kg 21.6-m-span Gossamer Penguin was used as a test bed, making a low-altitude 2.6-km solar flight in August 1980. The 98.6-kg 14.3-m-span Solar Challenger was developed for long flights in normal turbulence. Stressed for +9*g* ultimate, it is constructed almost entirely of plastics and filamental composites. With a 55-kg pilot, it sustains level flight on a minimum of 1400 W photovoltaic power in calm conditions. Ninety-four purely solar-powered flights were made in 1980-1981, culminating in a 262-km, 5-h 23-min flight from France to England on July 7, 1981. Maximum flight duration of over 8 h and altitude in excess of 4 km MSL were achieved in tests in California in May 1981. Maximum level flight speeds of 19.7 m/s were achieved in Europe with 2500 W of developed photovoltaic power.

Introduction

THE aim of the AeroVironment Inc. solar aircraft program, sponsored by the DuPont Company, was to make some pioneering and dramatic piloted solar-powered flights and thus increase people's awareness of the potential of photovoltaic energy as an alternative energy resource.

The first unmanned, controlled, solar-powered flight was made in 1974 when Sunrise II, a remotely piloted solar aircraft, flew to an altitude of over 5 km. Sunrise II was designed by Robert J. Boucher of AstroFlight, Inc., who has served as a key consultant on the Gossamer Penguin and the Solar Challenger.

The main aircraft of our solar program is the Solar Challenger, designed for the specific task of safely making long flights in normal, turbulent, sunny weather. As a stepping stone toward development of the Solar Challenger, we applied solar power to an existing airplane, the Gossamer Penguin, a 3/4-size version of the Gossamer Albatross II. The significant dimensional features of these aircraft and the initial Gossamer Condor are shown in Table 1.

Gossamer Penguin

Configuration

The Gossamer Penguin (Fig. 1) is an externally wire-braced, single-place aircraft of extreme light weight, with an electric motor drive replacing the foot cranks of its human-powered predecessors. A further modification, to improve yaw/roll response of the Penguin and free one hand for power control, was to add foot-pedal control of the wing warp system in lieu of the hand-operated warp control used on the Albatross. This aircraft served as an expedient test vehicle which could be expected to fly with the relatively small number of photovoltaic cells available to us at the start of the program.

The power plant was provided by AstroFlight, Inc. (Venice, California), and consisted of an "Astro-40" double-brush, dc electric motor and two-stage 27-to-1 belt drive reduction, coupled to a 5.17-to-1 chain drive at the airframe interface, for a total gear reduction of from 133 to 1. Nominal motor speed was 12,500 rpm.

The energy source for the motor during initial flight testing and pilot training periods was a battery of 28 "D"-sized nickel-cadmium cells weighing approximately 3.6 kg. Control of the battery power was effected by a transistorized series regulator with an emergency "kill" switch actuated by a lanyard attached to the pilot's right wrist. For solar-powered flights, the batteries were removed and a panel of 3920 solar cells [2240 (2×4)-cm, 700 (2×6)-cm, and 980 (2.4×6.2)-cm cells] was installed, capable of producing 541 W of power in an Air Mass 1 (AM-1) environment (equivalent to average conditions of clear sky of low turbidity and sun directly overhead, 100 mW/cm^2). The solar cells were manufactured by Spectrolab, Inc. Solar panel fabrication, testing, control, and instrumentation were provided by AstroFlight, Inc., which also supplied some of the cells. The remaining cells for the Gossamer Penguin (and all for the Solar Challenger) were rejected cells obtained from the U.S. Air Force via a loan from NASA to AeroVironment Inc.

The cells were arranged in four discrete subpanels with individual switches for each. This electrical subdivision obviated the need for the electronic control (whose heat sink weighed ½ kg) used with the batteries. This digital power control of the electric motor was made possible by the self-limiting short-circuit current characteristic of the photovoltaic cells, which reduces inrush current to a maximum of approximately 25% greater than that for maximum power. The fragility and limited controllability of the airplane required flying only early in the day when wind and turbulence were low but sun angle was also low. Therefore it was necessary to have the cells mounted on a panel which could be tilted toward the sun, and only flights headed north or south were feasible.

Instrumentation for the Penguin included airspeed, voltmeter, and ammeter. The voltmeter was located on an external wing wire and the ammeter on the battery pack in positions where they could be read by a ground-crew member; they were ultimately removed for the solar-powered flights.

Weight of the Penguin without the solar panel installed was approximately 23.5 kg. The solar cells weighed 4.3 kg. Total weight for the panel, including support structure and wiring, was 7.3 kg, producing an empty weight for the solar-powered craft of 30.8 kg. Wing area was 27.6 m^2 and the canard stabilizer area was 3.25 m^2. The stabilizer was 5.5 m ahead of

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Table 1 Significant parameters of the ultralight aircraft

Name	First flight, yr	Total weight,[a] kg	Weight without pilot, kg	Wing span, m	Wing loading, kg/m^2	Cruise speed at sea level, m/s	Minimum power to propeller, W
Gossamer Condor	1977	96	32	29.3	1.36[b]	4.5	246
Gossamer Albatross	1979	97.7[c]	33.7	28.7 (No.1) 29.3 (No. 2)	2.06[b]	5.4	190
Gossamer Penguin	1980	68-75	31	21.9	2.33-2.57[b]	6.6	220
Solar Challenger	1980	133-156	89-92	14.3	5.32-6.32[d]	8.5-16.1	1050

[a]Weights varied during development. Minimum used for minimum power estimate. [b]Assumes stabilizer operates at 1/2 the lift coefficient of the wing; 1/2 the stabilizer area is added to wing area for wing loading calculations. [c]As flown across English Channel. [d]Assumes stabilizer carries its own weight (12 kg); wing loading calculated from wing area and remaining weight.

Fig. 1 First solar-powered flight, May 18, 1980.

the main wing (proportionately farther out than on the Albatross).

Penguin Flight Test

The tests of the Gossamer Penguin were in two parts: 1) battery-powered flights to determine power required to fly, optimize the airframe/propulsion system, and train the pilot; and 2) solar-powered flights to demonstrate integration of solar power into an airframe.

Two pilots flew the Penguin for these tests. The first was 13-year-old Marshall MacCready, whose very light weight, 36.3 kg, permitted conveniently slow flying speeds, and the second was a lightweight adult (Janice Brown, weight 44 kg) who would serve as the official project pilot. Safety requirements dictated that the flight altitude never exceed 5 m.

To permit maximum utilization of the power from the solar cells, it was required to match the power curve of the motor to the power curve of the solar cells, while still retaining propeller efficiency. This required determining the optimum gear ratio and propeller pitch angle, and so a propulsion test rig was constructed. This rig, mounted to the front of a van, supported the fuselage and propulsion system approximately 6 m ahead of the vehicle in a manner that permitted measuring the thrust developed by the propeller at the 6.5 m/s optimum flying speed of the Penguin, while also monitoring the voltage and current requirement of the motor.

First flights at Shafter, California, on battery power, without the panel, took place on April 7, 1980, with Marshall MacCready as the pilot. After 50 battery powered flights, on May 18, 1980, the batteries were removed and the solar panel hooked up, and he made the first brief (about 30 s) climbing solar-powered flight. We moved to NASA-Dryden Flight Research Center in late July and finished the testing, and Janice Brown performed a 3-km public demonstration flight of 14 min on August 7, 1980.

Test Results and Conclusion

In the best of summer sun conditions with no more than moderate turbulence, at speeds within ±5% of the minimum power speed of 6.5 m/s, and with propeller pitch accurately set, vehicle aerodynamic efficiency permitted sustained flight, but just barely.

It is instructive to consider the stability/control characteristics of the first three types of aircraft[1] listed in Table 1. The 29.3-m-span Gossamer Condor had high drag, flew slowly (about 4.3 m/s), and in its final configuration proved to be quite docile and to perform nicely coordinated turns. The 29.3-m-span Gossamer Albatross was more streamlined and faster (flying about 5.2 m/s) and had similar moments of inertia but, because of the decreased area of its lifting surfaces, had less damping and smaller apparent mass effects; it was distinctly more slippery to fly, and had somewhat less tendency to perform well coordinated turns. The 21.9-m-span Gossamer Penguin, with its much smaller wing area but only slightly lighter gross weight, flew faster still (about 6.5 m/s), had lower inertias and less damping, and seemed to be on the ragged edge of stability and controllability. In summary, the particular configuration of these Gossamer aircraft served well for their intended roles but does not seem to be a good basis for higher performance vehicles; the Gossamer Penguin represents about as far as the design can be pushed.

Some specific conclusions resulting from the program follow:

1) A variable pitch propeller is a must for any practical solar-powered aircraft.

2) The stability/controllability of the Gossamer Penguin configuration is marginal at best and should not be the starting point for design of faster and heavier vehicles.

3) Thermal expansion joints are required to prevent buckling of solar cells when heated over a high range of ambient temperature.

4) Acrylic-based adhesive transfer tape is far superior to spray contact cements for attaching solar cells to a Mylar¶ film and may be released by heating the solar cells with a heat gun (although the process is difficult and considerable cell breakage can be anticipated).

5) A shock-absorbing landing gear is required to minimize cell breakage.

6) An aircraft should have enough excess power to maintain level flight in anticipated downdrifts near the ground.

7) Engine cooling requires careful consideration where the need for light weight and slow flight speed place severe demands on the cooling system.

8) The heating of photovoltaic cells mounted on the surface of a wing has a significant impact on available power and must be considered in predictions of power available, particularly for high-altitude flight.

Solar Challenger

Configuration

The Solar Challenger, with a 14.3-m-span cantilever wing (Figs. 2 and 3), is designed as a rugged 6g (design load) airplane with controllable-pitch propeller in front, stabilizer and fin in the rear, and normal three-axis controls. Gross weight

¶Mylar, Kevlar, and Nomex are DuPont trademarks.

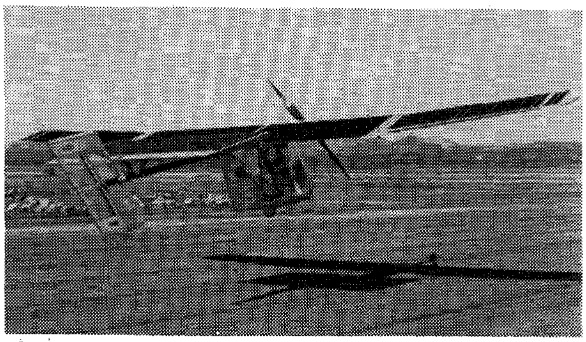

Fig. 2 Solar Challenger on first solar-powered takeoff, November 20, 1980, El Mirage Airport. 16,128 solar cells are visible on the top of wing and stabilizer.

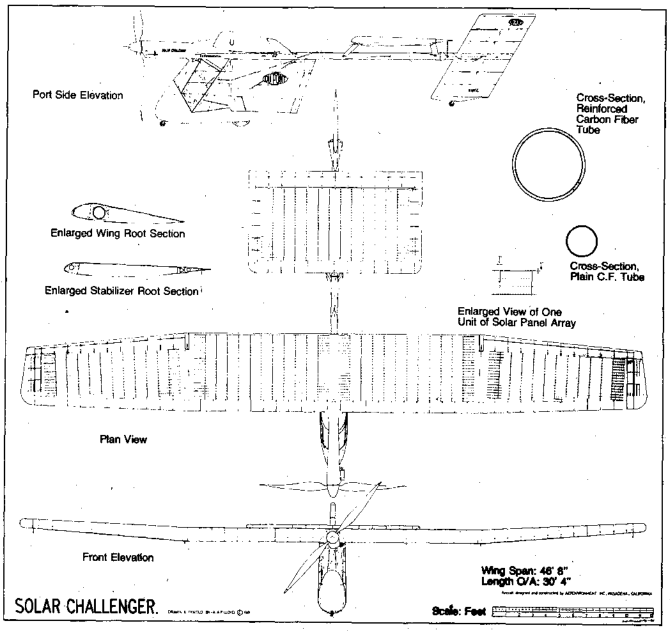

Fig. 3 Three-view drawing of Solar Challenger.

with a 44-kg pilot on board is 133 kg. It has an unusual appearance because the stabilizer is huge and the wing area large, so as to provide enough surface area for the 21.9 m^2 covered by 16,128 solar cells.

The large propeller, required for propulsive efficiency (estimated to be 86%) at low speeds, dictates the deep fuselage pod. Placement of the propeller on a boom well ahead of the wing, and use of an elevated horizontal stabilizer and a displaced, swept vertical stabilizer, are the result of iterative studies to maximize the solar incidence over the widest variety of sun angles and to avoid shadows on the cells. A cantilever wing is used. However, external drag and yaw brace wires were added to prevent flexing of the wing in the fore/aft plane, which was determined during initial load tests to cause buckling of the trailing edge and, potentially, breakage of solar cells.

The aerodynamics of the Solar Challenger are relatively standard, although some details have called for unconventional techniques. It was considered desirable that the upper surface of the wing and stabilizer should be flat over the major portion of the chord to minimize any installation problems with the solar cells. For the wing, an airfoil with an exactly linear last 85% of the upper surface was developed, designed to have attached turbulent flow at a lift coefficient of about 1.0. This airfoil, developed with the aid of an AeroVironment computer program, has performed very well in flight, and in-flight tests exhibited a maximum lift coefficient of about 1.4 with very docile stall characteristics. The airfoil, designated Lissaman-Hibbs 8025, is shown in Fig. 3. For the stabilizer, a flat upper-surface airfoil was developed, intended to have some laminar flow on the lower surface at lift coefficients near zero. This airfoil, Lissaman-Hibbs 8230, appears to perform according to these design requirements.

Standard, simple longitudinal stability computations were made. The static stability margin was set at 1% mean aerodynamic chord ahead of the neutral point, which was calculated to be at 37.5% of the wing mean aerodynamic chord. Because of the low relative mass of the aircraft, the maneuver point was estimated to be about 45% chord aft of the wing leading edge. The elevator and rudder were sized mainly by comparison with average proportions for comparable aircraft, and calculations indicated that control would be satisfactory. Aileron size was a compromise between photocell area (since there were no cells on the ailerons) and roll control. Because the proportions of the aircraft appeared relatively conventional, no dynamic stability calculations were performed. The propeller aerodynamic design was developed by Bart Hibbs at AeroVironment using an in-house computer program. The propeller airfoil is an Eppler 193. The propeller design concept is based on the optimal loading techniques employed by E. Eugene Larrabee, used by his group in the design of the propellers for the Gossamer Albatross and Gossamer Penguin.[2]

Propulsion System

During the initial winter flights, the Solar Challenger was powered by a 3.5-kg, permanent (Barium ferrite) magnet, dc electric motor (designated Astro 2500). Nominal motor speed was 7000 rpm and desired propeller speed was 300 rpm, necessitating a 23.3-to-1 gear reduction. This two-stage reduction was accomplished by a 4.5-to-1 belt drive and a 5.17-to-1 chain drive to the propeller shaft.

For summer flights a larger motor was developed. This improved motor essentially consists of two motors of the original size, mechanically connected in tandem. The magnets are Samarium Cobalt for increased flux density and resistance to de-Gaussing and thermal "runaway" problems. The armature is wound with fewer turns of heavier gage wire; and the brushholders, brushes, commutators, and cooling fan impellers are all of improved design. To enhance cooling, the motors are located outside the pylon fairing.

The propeller pitch is manually variable from full feather to near-flat pitch to optimize motor speed and match solar cell output characteristics for maximum power.

The 16,128 rectangular silicon solar cells (300 μ thick) were installed on the upper surface of the wing and stabilizer in strings of 144 cells in series and three cells in parallel, held in place with an adhesive transfer tape. This paralleling of individual cells permits the current to bypass a broken cell without overloading adjacent cells or shutting off the current from the remaining 143 good cells in that series. Nominal voltage of the system is 66 V, varying with cell temperature. The 144×3 cell strings were paralleled to form five discrete panels of cells, four on the wing and one on the horizontal stabilizer, covering 68% of the total aircraft planform.

Each string is connected through a diode to the panel bus to permit testing individual strings for current output, and also to prevent an internal short in one string from shorting out all the other strings. Each panel is controlled by a manual toggle switch and protected by a 10-A fuse.

Splitting the power supply into five parts limits the inrush current to an acceptable level at engine startup, and permits selection of power levels for taxiing and descent. Normally, however, all five panels are used and power is regulated by propeller pitch control.

In the final cross-channel configuration, the left and right tip, and left center wing panels are fed to the front motor; the remaining two panels power the rear motor. Cockpit instrumentation for the propulsion system includes a power meter (interconnected with the front motor only to minimize line losses), an engine speed indicator, and two ammeters—one for each motor. The proper propeller pitch (and thus motor speed) are determined by optimizing the power level while the ammeters show the relative power levels carried by the two motors.

Structure

The structure of the Solar Challenger uses techniques developed for the Gossamer aircraft, aerospace composites, and model building. Unlike its Gossamer ancestors, the Solar Challenger must fly safely at high altitude in normal, daytime turbulence. The design criteria were therefore modified to put safety ahead of lightness in structural design. In all areas where structural integrity was considered to be critical, a conservative design approach was used. Where failure of an item was not considered hazardous to the pilot's safety, judgments were made on a less conservative basis with greater emphasis on lightness.

All primary flying surfaces and controls were considered flight-safety critical. The propulsion system, fuselage and engine fairings, landing gear, and instrumentation were considered not critical. It was always assumed that in respect to potential landing sites the Challenger would be flown as a glider because power could be lost at any time owing to weather or system failure.

Design loads for the Challenger were developed from Refs. 3 and 4. The main structure was designed to limit loads of $+6.0$ and $-4.0g$ with a 1.5 ultimate factor, and the control system with a 3.0 ultimate factor. In addition, the fuselage was designed to withstand $+4.5g$ vertical and $1.0g$ lateral landing loads, as well as $9.0g$ crash loads (forward and down).

The Challenger design utilizes filamental composites where strength is required and utilizes the most lightweight and easily formable plastic where strength is not the primary criterion. Because of its very high stiffness-to-weight and strength-to-weight ratios, graphite fiber/epoxy was chosen as the principal structural material, compressive strength being the limiting parameter in most elements. Kevlar aramid fiber strands, braid, and cloth are used as tension elements and as tube reinforcement because Kevlar is very light, strong, and unusually tough. Kevlar has very high tensile strength and modulus for its weight, making it ideal for internal bracing. Mylar plastic film is used as the outer covering of the Challenger because it is very lightweight and aerodynamically clean. Because it can be applied so that it heat-shrinks more in the spanwise direction, it is easy to get a smooth, tight wing surface with a minimum of sag between the ribs.

Perhaps the single most important structural component of an aircraft is the wing spar. While appearing simple and monolithic at first glance, the Challenger's spar is actually a fairly complex structure. The spar is manufactured from unidirectional graphite/epoxy preimpregnated tape, Nomex honeycomb, and Kevlar 49 fabric laid up wet with epoxy resin. The basic structural tube (178 mm i.d.) contains the graphite tape in spiral wraps at ± 45 deg to handle torsional and bending shear forces. Bending tensile and compressive loads are carried by multiple layers of graphite caps with filaments oriented lengthwise, tapered in width and number of plies, located on the fore and aft and top and bottom sides of the spars.

The tube wall is stabilized by the addition of Nomex honeycomb bonded to the graphite by a mixture of epoxy resin and phenolic microballoons and then overwrapped by two plies of Kevlar fabric/epoxy resin. Stabilization of the graphite tubes by this means permitted an order of magnitude higher allowables for the graphite. In addition, the Kevlar fabric, because of its ability to retain its tensile strength even after failure of the laminate, reduced the likelihood of catastrophic failures.

Peter Boukidis served as structural consultant and assisted in developing the analytical techniques for determining allowable loads, while Blaine Rawdon, an AeroVironment staff engineer, performed most of the iterative analysis which actually determined the thickness of carbon required in the spars.

Weight of the 14.3-m wing spar, including receiver joints, which allowed the two 3.8-m tip panels to be removed for transport, is 13.6 kg. The tip spars have an inside diameter of 127 mm as does the tail/nose boom, which is of similar construction.

The stabilizer spar construction is similar to the wing spar, except the reduced diameter permits use of polystyrene foam plugs at 150-mm intervals for stabilization in lieu of the honeycomb sandwich. The horizontal stabilizer has a spar at the front and at the rear because of its large chord and short span, also because of the need for fore and aft hard points for attaching the stabilizer to the boom.

Rib design is similar to that of the Albatross and Penguin, except for an improvement to facilitate construction by utilizing Kevlar fabric doublers on the shear web at the spar instead of builtup plywood and graphite strips previously used.

Improvements were also made in the leading and trailing edges of the flying surfaces. Leading-edge formers were hot-wire-cut polystyrene foam sections that fit between the ribs, improving the maintenance of the airfoil section. The Challenger trailing edges are a fiberglass and foam sandwich.

To minimize flexing of the solar cells, polystyrene foam sheeting (6.25 mm thick) is used between the ribs on the upper surface to stabilize the 12.7-μ Mylar film which covers all the flying surfaces.

Fuselage tubing is graphite overwrapped with Kevlar fabric, which contains the graphite splinters in a failure and also increases the allowable crippling stress of the graphite fiber.

The main landing gear consists of a Zytel ST bicycle rim (with thornproof tube and tire) especially built up with an extra-wide hub on a trailing arm (tetrahedral space frame) and suspended by twisted Nylon webbing and Kevlar 29 braid. The relatively low modulus of the Nylon produces a soft ride during normal taxi and landing operations, while the higher modulus Kevlar acts as a backup when the Nylon is overextended by hard landings.

The propeller blades are made of graphite fabric/epoxy laid up wet over a high-density polystyrene foam core. Unidirectional graphite spar caps also run the length of the blade to carry bending loads and improve bending stiffness of the propeller.

To minimize weight and simplify routing, control line material is required which has a high stiffness/strength-to-weight ratio, yet remains flexible, durable, and resistant to ultraviolet degradation, abrasion, and weathering. Kevlar fiber has a high stiffness/strength-to-weight ratio, but in braided form loses much of its modulus owing to the geometry of the fiber orientation. A unique, patented process developed by Synthetic Textiles, Inc., of Ventura, California, interlocks unidirectional strands of Kevlar 29 yarn and then over-braids this core with Dacron cord to protect the Kevlar from snagging, abrasion, and ultraviolet degradation, solving the problem.

Control surfaces are actuated by control lines to bell cranks attached to graphite torque tubes, which also serve as spars for the surfaces.

Testing

Tests to gain empirical data on strength of materials were performed throughout the development program. The data allowed us to form empirical curves which were used for all of the main structural calculations. In addition, tests were performed on the following subassemblies.

Small Wing Test

To test the wing secondary structural system, a 2-m-span wing of full size chord was built using a different structural configuration for rib, leading edge, and sheeting in each bay. The upper covering was attached with various adhesive configurations in each bay, and solar cells were attached at strategic locations. This wing was mounted on a fixture atop a van and driven at 28 m/s at angles of attack from positive to negative stall without any failure.

Seat Tests

To minimize the possibility of injury to the pilot, the pilot's seat was designed to collapse under an excessively high g landing situation. Expanded polystyrene foam was cored out with multiple holes and tested for compressive strength to discover type of failure mode and load carrying capacity.

Tail and Fin Speed Tests

The tail surfaces were mounted onto a partially streamlined support and installed on the roof of a van for high-speed tests along the runway at the local airport. A few initial test runs were performed to check the stability of the test rig before a "test pilot" sat atop of the van, wearing a safety harness, to operate the control surfaces via a joystick and rudder pedals. Speeds were then increased from 13 m/s upwards, with the control surfaces operated rapidly to full deflection. The maximum design flight speed for the Challenger is 19 m/s and the van reached speeds up to 28 m/s without any flutter.

Wing Speed Tests

A similar test was performed with the complete wing mounted on top of the van and also driven to speeds of 28 m/s with a "test pilot" operating aileron controls. Sandbags were used to simulate the weight of solar cells. Minor buckling of the fiberglass trailing edge was observed due to drag loads at these high speeds. To counteract this effect on the airplane, bracing wires were added fore and aft. Further tests were performed with the tip panels removed to test the tolerance of the Mylar covering to air pressure. An air scoop was fabricated to force air into an open compartment of the wing under the center panel. The covering held up perfectly under this test.

Static Load Testing

A bending and deflection test was performed on all flying surfaces to measure how the design and construction stood up under load. The flying surfaces were mounted horizontally in support fixtures and progressively loaded with 4-lb sandbags with weight distributed spanwise along the structural spars. The wing was tested to 84% of its limit load positively and 75% of its limit load negatively. All other flying surfaces, controls, and tail boom were tested at 100% of their design limit load.

Tow Tests

The first outing for the Solar Challenger was at Santa Susana Airport on October 30, 1980 when the assembled aircraft was towed along the runway to test nosewheel castering, taxiing, and braking; to verify c.g. location and pitch controllability; and to familiarize the pilot with the controls. During this outing, it achieved a brief test hop of a few seconds while being towed behind three running crew members.

Battery-Powered Flight Tests

Prior to installation of the solar cells on the wings, a battery of 120 rechargeable nickel-cadmium cells was installed in the fuselage, along with a digital power control panel for preliminary flight tests. A highly experienced, although heavier (over 67-kg) test pilot, Stephen Ptacek, was utilized for initial checkout of the aircraft and training of the light-weight official project pilot, Janice Brown. A gradual flight test procedure was followed to explore each regime before expanding the envelope. Initial procedures involved taxi tests to familiarize pilots with the power control, propeller pitch control, flight controls, and braking systems. Many low-altitude flights were made with ballasting to vary the c.g. from 25 to 37% of MAC and with stabilizer incidence angle varying from +1 to +4 deg. The aircraft was found to be stable and with adequate control authority with any combination of the above parameters (calculated neutral point is 37.5% of MAC).

Although the stabilizer supports were designed to permit in-flight pitch trim, it was decided, based on the above tests, that pitch trim was not required, and the incidence angle was fixed at +1 deg (main wing incidence is +4 deg).

A small radio and a hang-glider-type parachute weighing less than 2 kg were installed in the aircraft. The parachute is designed for deployment at altitudes as low as 45 m to permit descent of the pilot and airplane together in the event of a structural failure. By the end of the third day, Ptacek had verified docile handling characteristics and adequate control response in up to 30-deg banked turns and straight-ahead stalls. Although loss of aileron authority was experienced during stalls, the nose dropped straight ahead and wings were easily held level using the very effective rudder.

The remainder of the battery flight test period (total of one week) was dedicated to putting more time on the pilot and airframe. A total of 49 flights, totaling 4 h 58 min of air time, were accumulated. Although a maximum of approximately 20 min of battery power would be obtained from one charge, on the last day Brown made a flight of 1 h 32 min by shutting off the power and feathering the propeller after a 10-min climb and soaring to 400 m above ground level (AGL).

Solar-Powered Flight Tests

By November 20, 1980, the battery pack and controller had been removed; the wings and stabilizer had been mostly covered with 22.7 kg of photovoltaic cells and associated wiring, and the Solar Challenger had been transported to El Mirage gliderport near Victorville, California. At 1:09 p.m. the Challenger, with Brown at the controls, rolled down Runway 4 into a 5-m/s headwind and lifted off, making a 2-min 50-s flight down the runway (see Fig. 2). Estimated power available during this flight was 1750 W.

Hampered by high winds of adverse direction and high clouds during the next week of testing at El Mirage, only 22 flights were accomplished with total air time of just 1 h 2 min.

On December 2, 1980, the Solar Challenger began making short test flights at Marana Airpark, northwest of Tucson, Arizona. Marana is surrounded by Saguaro cacti, and the angle of climb of the Solar Challenger in December was less than its power-off glide slope. Therefore it could not be safely flown in a straight line away from the airport. The Challenger required at least 300 m altitude to safely make the next available landing spot in the event of a power failure. Also, because of the low sun angle, the aircraft would lose altitude when flying back towards the sun. Thus it was necessary to utilize thermals at the north end of the runway to gain sufficient altitude. A vehicle was driven in the dirt off the runway to stir up dust and break loose thermals, producing visible columns of dust, which the pilot could fly directly into and begin circling as low as 50 m to gain altitude.

On December, 6, 1980, under 85% cirrus and alto-cumulus cloud cover, a 100-km flight was attempted. Taking off at 10.57 a.m., pilot Brown thermaled to 670-m AGL by 11:38 a.m. and headed north towards Phoenix. Chased by heavy rainstorms from the west and southeast, the Challenger more than once relied on thermals alone to regain safe altitude before finally being rained down at 12:52 p.m., only 24 km from takeoff.

Damage to the propeller sustained during that off-field landing (which caused the propeller to strike the fuselage fairing in a flight attempt the next day), along with continued predictions for inclement weather and budgetary constraints, forced us to abandon further flights for the year. Twenty flights totaling 4 h 45 min were completed at Marana in December.

Improvements in the propeller pitch control system and motor cooling, as well as extension of the nose boom to locate the propeller 30 cm farther forward (to minimize vibratory loads induced by aerodynamic interference with the fuselage, and also to lessen the chance of a damaged propeller striking same), were tested at Marana in January 1981. Sixty-nine flights with a total of 6-h 4-min engine time were accumulated during these tests, most by Janice Brown, some by test pilot Steve Ptacek. Several tow tests were made with Ptacek holding the towline with one arm through an open cockpit door to check streamlines about the propeller and fuselage, and also to check for flutter at high speeds.

Based on the Arizona test results, the Solar Challenger was prepared for the summer France to England flight by installation of 1) the improved tandem motor previously described, 2) a 720-channel vhf radio (to replace the two-channel radio), 3) a transponder, and 4) a turn rate gyro (in addition to the airspeed, compass, variometer, and motor instrumentation already covered). Also installed were two 60-unit strings of solar cells to power items 2, 3, and 4, as well as a small battery to provide ½-h emergency operation of same (new empty weight: 98.6 kg).

Following a 6-h green run of the motor installation in the lab, the Solar Challenger was taken back to Shafter, California, for final system and pilot checkout in May 1981. A total of 23-h 19-min air time was accrued in 13 flights during these tests, including three flights in excess of 6 h duration and above 3 km. The longest flight (8 h 19 min) covered a ground track of over 320 km and reached altitudes of 4 km in spite of heavy cirrus cover during mid-day and a 61-kg pilot (Ptacek).

France to England Flight

In early June the plane, in its trailer, was transported from Los Angeles to Paris in a Boeing 747 freighter, courtesy of Flying Tigers. Test flights in France commenced at Pontoise-Cormeilles Airport, 40 km northwest of Paris, on June 12. On June 14, Ptacek made an 8-km flight, terminated by involvement with the wake and collision hazard from an overzealous observation aircraft (15 m/s crosswinds at altitude would have precluded the Solar Challenger's reaching England in any case). The weather remained uncooperative, with clouds and strong north winds, permitting only a few test flights (including 4¼ h, 2.9 km AGL on June 22). The plane was trailered to Manston RAF Base in eastern England to take advantage of the northerly winds and a predicted break in the overcast for a flight from north to south. However, the break turned to rain and overcast skies subsequent to our arrival while the winds shifted to the southwest, permitting only a few test hops from Manston, so the plane was then returned to France.

On July 7, the Solar Challenger, piloted by Stephen Ptacek (dieted down to 54.5 kg in his wetsuit), took off from Pontoise-Cormeilles Airport at 9:28 GMT and landed at Manston RAF Base at 14:51 GMT, a straight-line distance of 262 km. Maximum altitude reached during the 5-h 23-min flight was approximately 3.5 km MSL.

The goal had originally been to fly from near-Paris to near-London. This destination proved impractical because of air traffic control realities in the heavy air traffic région around London; hence the decision was made to shift the destination to Manston. The first 3 h of the July 7 flight were at a ground speed of 10.5 m/s, climbing to the northwest, crossing the coast at Le Treport. Thereafter, the trajectory was nearly straight to the destination, and ground speed almost doubled (true airspeed, 19.1 m/s maximum, some tail wind component). The only problems were encountered with the wakes of other aircraft during the first portions of the flight: a helicopter and a Cessna 172 which both operated close to the Solar Challenger, and a large four-engine turboprop aircraft whose wake tossed the Solar Challenger about violently, giving high positive and negative loads, 12 min after the vortex wake was formed.

Lessons Learned

Performance

The goal was to make the Paris to England flight, not perform basic research, and so there has been little opportunity for really quantitative measurement of power available and performance of the Solar Challenger. Thus there were no reliable direct observations of performance, but clues were gleaned from portions of various flights. The best observation was on the long July 7 flight, in clear air, at about 3.3 km altitude. In the cruise attitude, the observed power was 2500 W, and the power at climb attitude was 2800 W. Considering attitude and geometry, this corresponded to about 11.6% efficiency for the solar cells. The amount by which the cells heated above ambient is not known, but the slow speed certainly permitted significant heating, which reduces solar cell efficiency by from 0.4 to 0.5%/°C increase. The maximum power from the solar cells with bright sunlight and ideal sun angle is estimated to vary from 2550 W at sea level to 4100 W at 15 km.

For the long duration level cruise portion of the July 7 flight, the true airspeed was 19.1 m/s at 3.3 km altitude, for the 154-kg aircraft. For these conditions, our best estimate for motor efficiency is 0.78, reduction gearing is 0.95, and for propeller efficiency is 0.85. The equivalent glide ratio for a feathered propeller can then be calculated from the 2500-W electric input and turns out to be 18.6:1. Performance estimates for the maximum climbing mode near sea level at indicated airspeeds around 9 m/s were made on portions of various flights with the light (133-kg) vehicle, especially during winter takeoff maneuvers. The propeller efficiency was lower at these slow speeds, say, 0.75, while the motor efficiency was higher because a different motor was in use, say, 0.82. The observation that about 1400 W would keep the vehicle aloft in smooth air just out of ground effect then yields an equivalent glide ratio at the minimum sink condition of 14.3:1. With a standard parabolic performance ratio curve, this would correspond to a maximum lift/drag ratio of 15.7 at an airspeed of 11.8 m/s.

For the lower 7 km, the increase in airspeed and hence power required almost exactly balances the increase in power available from the solar cells due to cooler temperature and stronger radiation. Figure 4 shows the predictions of the altitude performance of the Solar Challenger. The most significant feature is that the maximum climb is achieved near 9 km. The plane climbs slowly, but can reach extreme

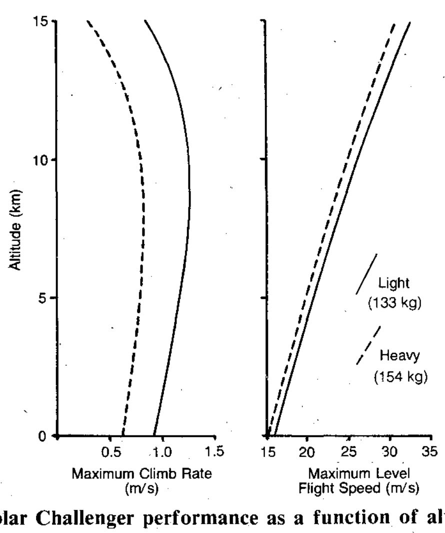

Fig. 4 Solar Challenger performance as a function of altitude and weight.

altitudes if the life support system for the pilot does not add too much weight. When calculating performance in a particular flight mode, the cell orientation relative to the sun is critical. At the lowest speed, in level flight, the average cell angle is tilted 18 deg toward the rear; at 50% higher speed the angle is 11 deg. Climb and glide angles must also be taken into account when considering sun interception angles.

The accuracy of the observations is not such as to justify careful analysis of performance aerodynamics, but the observations suggest that 1) the span efficiency factor is not below 0.9, and 2) the parasite drag at wing C_L of about 0.3 is low, perhaps even below 0.008 for the wing in spite of the rough upper surface where the solar cells are mounted.

It is also worth noting that clouds did not prove as debilitating as first assumed. In fact, the scattering/reflecting effect of clouds surrounding but not blocking the sun would sometimes produce solar intensities in excess of 100% AM-1.

Aerodynamics

Although a slight weight penalty was paid in supporting the oversized stabilizer, a bonus was realized in the dynamic response of the aircraft. Stall recovery was so rapid that it was more efficient to fly the airplane right at stall during climb-out, because the height loss due to stall recovery was more than compensated for by the improved sun angle (when flying away from a low sun) and the reduced power required to fly.

The propeller pitch control system proved to be a very effective drag brake with the power switches off. Varying feather angle could produce lift-to-drag ratios from the maximum down to a minimum of an estimated 5 to 1 (at high flight speeds).

Proximity (10 cm) of the propeller to the fuselage in the initial flight configuration created an aerodynamic pulsing which caused shaking of the fuselage as well as high dynamic loads in the propeller and its pitch control system. This pulse could be felt by the hand up to a distance of from 15 to 20 cm aft of the rotating propeller blade. Relocation of the propeller plane 30 cm farther forward drastically reduced vibratory loads.

Application of Solar-Powered Aircraft

An aircraft could be built which would climb during the daylight hours, storing solar energy in potential form by altitude gain and in chemical form by charging batteries. By careful design, this energy could be sufficient to keep the vehicle aloft at night so that the cycle could be repeated each day. Some preliminary calculations for an unmanned RPV have indicated that such a mission could be achieved using currently available photovoltaic technology, battery systems, construction methods, and aerodynamics. It appears that such a vehicle would have a limited payload and flight speed but could serve a useful meteorological or survey function.

Acknowledgments

Figure 1 was provided by Ernest Franzgrote, who provided the prediction of cell output vs altitude/season/latitude/vehicle orientation throughout the solar program. Figure 2 was provided by Martyn Crowley.

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