Sunrise, the World's First Solar-Powered Airplane

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The design, construction, and flight tests of the world's first solar-powered airplanes, Sunrise I and Sunrise II, are discussed. Sunrise I made its first solar flight on November 4, 1974, and demonstrated for the first time that an airplane could fly on solar power alone. Sunrise I made scores of flights during the winter of 1974 and spring of 1975, finally being damaged in a windstorm. An improved version, Sunrise II, constructed in the summer of 1975, first flew on September 12. Sunrise II was 13% lighter, was aerodynamically cleaner, and had 33% more power than Sunrise I. Sunrise II was prepared for a high-altitude attempt to 50,000 ft on September 27, 1975. The aircraft climbed at a rate of 8,000 ft/h and was expected to reach 50,000 ft in 6 h. At an altitude of 17,200 ft, the command and control system failed, the aircraft was severely damaged, and the flight test program was terminated.

Introduction

THE concept of Sunrise,[1-5] a solar-powered vehicle of extended range and altitude, was a natural extension of the pioneering work done in the field of electric-powered, fixed-wing aircraft.[4] The use of solar power, although heavy in terms of watts per pound and expensive in terms of watts per dollar, has one singular feature: the energy source is inexhaustible. Since the solar flux at sea level is sometimes obscured by clouds, the solar-powered vehicle will seek the clear regions of the upper atmosphere, where it can bask in the unattenuated sun, free from high winds and atmospheric turbulence. Such an aircraft, operating above the normal airways, and remotely piloted, could fulfill many military and civil uses.

Sunrise was a proof-of-concept vehicle intended to demonstrate the feasibility of extended solar-powered flight at high altitudes. The present paper covers the design, construction, and tests of the Sunrise I and Sunrise II vehicles. The flight tests are covered in detail. Although extended solar flight was not attained, the Sunrise II set a world altitude record for solar-powered vehicles which, a decade later, still stands.

Five years later, the solar panels from Sunrise II were removed from the wings and attached to a single panel and used to power the Gossamer Penguin[6] manned solar airplane. The Cobalt 40 motor used to power Penguin was a direct descendant of the Cobalt 40 used in Sunrise II. The author used his experience gained in Sunrise to build the solar propulsion system (motor and solar panels) used in the Dupont Solar Challenger.[7]

The Air Vehicle

Configuration

The air vehicle is shown in Fig. 1. It is a high-wing monoplane propelled by a 0.6-hp motor driving a 30-in. fixed-pitch propeller. No ailerons are provided; rather the design utilizes a 6-deg dihedral coupled to a balanced rudder. Pitch control is effected by a rather small elevator attached to a normal stabilizer. The single-wheel undercarriage with tail skid and outrigger wires proved adequate in every landing. Takeoff was assisted by utilizing the stored energy in a stretched 50-m length of bungee cord attached with a drop-away hook attached to the landing gear bulkhead.

The wingspan is 32 ft, length 14.37 ft, height 3 ft, wing area 90 ft^2, and gross weight 22.8 lb. (Fig. 1).

Airframe

The Sunrise vehicle is a high-wing monoplane. The configuration is orthodox, and the areas and moments resemble a powered sailplane. Construction of the wing utilizes a box spar with spruce caps and balsa webs to take bending loads and a balsa sheeted D-tube leading edge to withstand torsion and fore-aft loads. The outer wing panels are removable by, and secured with, a single ¼-in. steel bolt at the main spar. The fuselage utilizes a Warren truss made of Douglas fir with ash blocks to take single-point loads, such as landing gear, wing, and tail attachments points. The entire framework is covered with mylar sheet attached with industrial adhesive and shrunk in place by the application of heat (Fig. 2).

Weight Statement

Table 1 shows that the vehicle was 0.4 lb over the design goal of 22.5 lb. This excess weight was caused by the requirement that the command and control batteries be doubled for the expected 14-h mission. The original 0.54 lb, 3 A-h battery, when tested, gave only 7 h of life as compared with the 12-h life expected. Other variations from the original design goal were solar array: 5 lb vs the 5.5 lb actual. The solar array had more power by 15% so that the specific weight was met. The propulsion subsystem consisting of a high-efficiency, ball-bearing, permanent-magnet motor; a belt speed reducer; and a 30-in.-diam wooden propeller was 2.1 lb as compared with the 2.6 lb anticipated. In summary, the actual weight was essentially as specified, with a slight overweight condition of 0.4 lb. This weight is remarkably light for a 32-ft wingspan machine having 90 ft^2 of wing area.

The Propulsion Subsystem

The propulsion subsystem consists of a high-efficiency, ball-bearing, permanent-magnet dc motor driving a timing belt speed reducer coupled to a 30-in.-diam, 16-in.-pitch, wooden propeller. The motor features a rare-Earth magnet and weighs 18 oz, yet produces more than 0.6 hp and was specifically designed and built for the aircraft. The complete propulsion system weighs only 2.1 lb, giving a specific weight of 3.5 lb/hp.

Load lines for the high-altitude mode (series array) and low-altitude mode (parallel mode) are shown in Fig. 3. The par-

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ticular propeller used matched the motor and array output at 35,000 ft. This limited altitude to 46,000 ft on September 27 and 52,000 ft on June 21. If the prop and gear ratios were adjusted to match at 50,000 ft, the vehicle altitude ceiling would be increased to 70,000 ft on June 21, the longest day of the year.

The Solar-Power Subsystem

The solar-power subsystem for Sunrise I consisted of six arrays of 2-in.-round solar cells. The array provided 400 W and weighed 7.25 lb. Not only was this 50 W underpowered and 2.75 lb over weight, the round cells simply refused to stick to the curved upper surface of the wing. The exposed edges of these cells increased the minimum drag of the airframe by 66%. In spite of these difficulties, scores of solar-powered flights were conducted with Sunrise I in the winter and spring of 1974-1975.

The power subsystem for Astro Flight's Sunrise II consists of four arrays of 1120 (2×4 cm) solar cells wired in series parallel to provide 37 V at 3.8 A each (Fig. 4). These arrays were attached to a 0.5-mil mylar substrate which, in turn, was attached to the wing structure with industrial adhesive (Fig. 5). The circuit was arranged to provide the motor terminals with either 15 A at 37 V or 7.5 A at 74 V. In addition, a booster bat-

Table 1 Weight statement—Sunrise II, lb.

Airframe		
Wing	7.71	
Vertical stab	0.47	
Horizontal stab	0.90	
Fuselage	1.83	
Airframe subtotal		10.91
Propulsion		2.10
Solar array		5.56
Command and control		
Command receiver	0.44	
Servoactuators (5)	0.60	
Sensors	0.39	
Encoder	0.32	
Telemetry transmitter	0.18	
Lithium battery	1.09	
Command control subtotal		3.02
Beacon (X-band)		1.29
Air vehicle gross weight		22.88

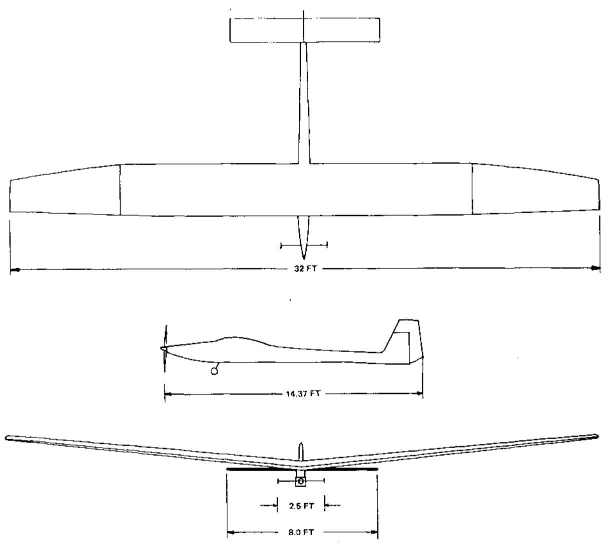

Fig. 1 General arrangement of Sunrise I and II.

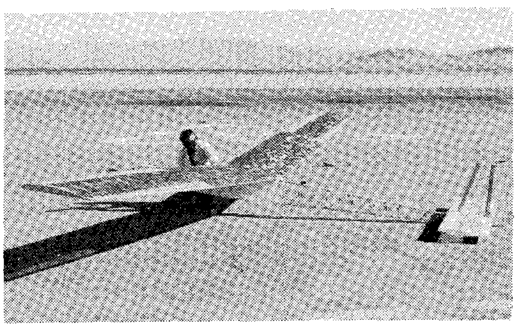

Fig. 2 Sunrise vehicle.

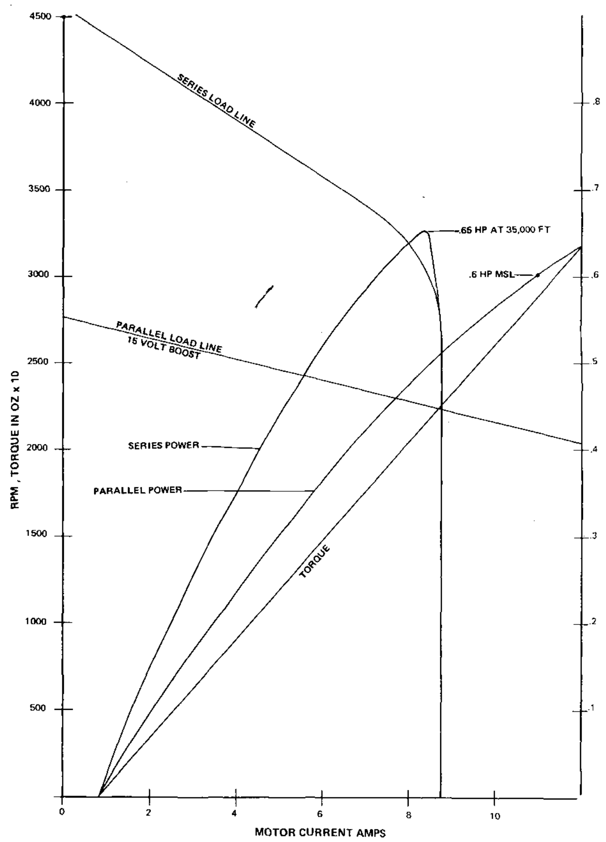

Fig. 3 Solar-power system performance.

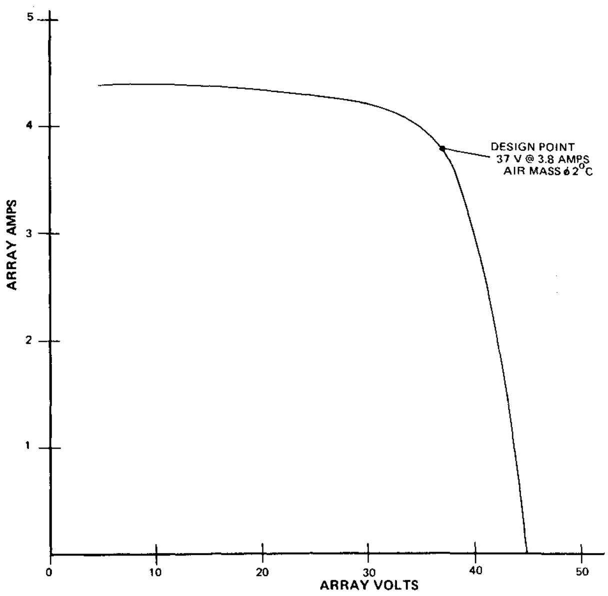

Fig. 4 Measured performance of a 1120-cell array.

tery of 15-V, 24-A-h capacity was provided as an aid in early morning launch, when the sun was low. The booster was designed to be jettisoned at 20,000 ft altitude. In actual tests the panel delivered slightly more power and provided 580 W maximum. It weighed 5.5 lb with all wiring, cabling, and connectors: the bare cells weighed 4.5 lb. The array worked well and the specific weight was 105 W/lb as compared with the design goal of 100 W/lb.

The Command and Control Equipment

The command and control equipment consisted of two basic subsystems. The control system used a top-quality 72 MC radio control set driving a 10-W power amplifier coupled to a vertical whip antenna. The control functions were rudder, elevator, motor on-off, array series/parallel, battery booster in/out, and battery jettison. These six functions were accomplished with five independent channels by combining the on-off and series-parallel functions on a single-output cam of the motor control channel. A link analysis indicates that the command range was reliable to 50 miles.

A second subsystem consisted of the airborne telemetry subsystem and the ground telemetry reception and data display subsystem. Seven quantities were measured by the aircraft onboard sensors. These were airspeed, propeller rpm, motor voltage, motor current, electronics compartment temperature, and two null indications of sun position that are sun left-right and sun to-from. These latter quantities were used to navigate the vehicle when out of visual range of the operator. No direct measurement of pitch was used, but airspeed was used to indicate pitch trim, and the elevator trim was adjusted to obtain desired airspeed for best climb. The vehicle was well damped in pitch and responded smoothly and rapidly to pitch trim changes. The navigation proved itself when the vehicle was lost to ground tracking for 20 min while the sun navigation system was successfully used to navigate the vehicle from last known position back to the launch location.

It should be noted that we were forced to build our own command and control systems because the standard military remotely piloted vehicle (RPV) systems were 20 times too heavy and 10 times too expensive.

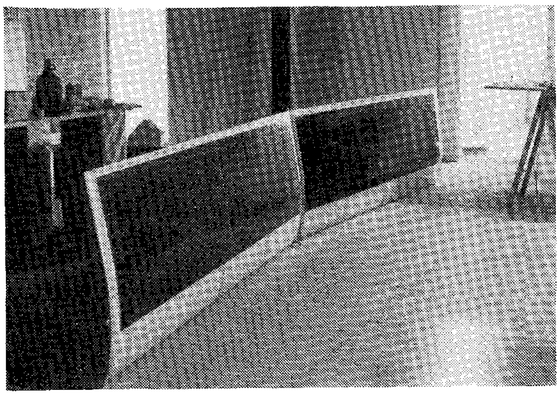

Fig. 5 Solar cell array on Sunrise II.

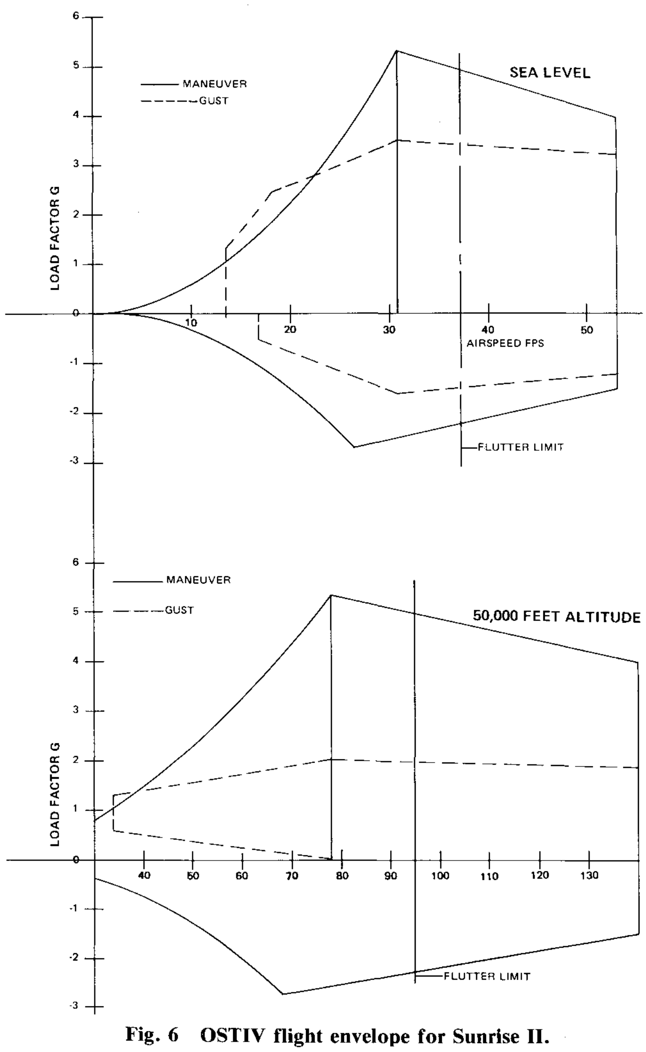

Fig. 6 OSTIV flight envelope for Sunrise II.

The Flight Envelope

The basic flight envelope for Sunrise II was determined using the Organization Scientifique et Technique Internationale du Vol a Voile (OSTIV) method as described in the document "OSTIV Airworthiness Requirements for Sailplanes," September 1971.[8] The results of these calculations are shown in Fig. 6. The requirements for sea level operation and operation at 50,000 ft altitude were calculated. Since the wing torsional stiffness resulted in a flutter speed limit of less than V_d, this speed is shown on the diagrams. According to these requirements, the vehicle was strong enough to withstand the normal rigors of flight, even in the presence of very strong gusts. And it did withstand these rigors for scores of flights; failures occurred only when the flight envelope was exceeded by a substantial margin.

The First Flight on Battery Power

The first flight of Sunrise I took place at Bicycle Lake, CA, on September 17, 1974. The vehicle was equipped with a 52-V nickel-cadmium battery to simulate the power of the solar array, which was then in fabrication. Takeoff was at first light at 6:00 a.m., and the plane climbed to about 500-ft altitude. Control was smooth, and the vehicle was well damped in all axes. To assess the specific climb performance, the motor was shut down and the vehicle allowed to glide until it was close to the surface; then power was reapplied and climb resumed for 1 min. The motor was then shut down again, and the cycle was repeated many times. Results of this flight indicated a power ratio of 8:1; that is, the power was turned on one-eighth the total time in the air. These data were used to confirm the expected sink rate and climb rate and power limited ceiling. Figure 7 shows the climb rate and power level (450 W) used and the sink rate achieved. A power ratio of 8:1 would allow the aircraft to maintain its altitude at 75,000 ft if it were not limited by the propeller overspeed to 60,000 ft. The test results were most satisfying since they demonstrated that the basic concept and aerodynamics were sound.

It is interesting to note that this flight took place at the same time that Irving and Morgan[9] were presenting their paper at MIT on the "Feasibility of Solar Flight."

Expected Performance of Sunrise I with Solar Power

Because the solar array was 2.75 lb overweight and behind the center of gravity, an additional 1.5 lb of lead ballast were required. This and other related modifications resulted in an increased gross weight of 26 lb. The climb performance at this late date in the year was expected to be much lower than that possible on the proposed summer flight. To complicate things, the solar array, which consisted of round disks cemented to the mylar skin, simply would not remain attached to the curved surface of the wing. These exposed edges were present over most of the wing surface and substantially increased the wing profile drag. Analysis of the voluminous raw flight data indicates that the aircraft minimum drag coefficient is increased 66% by this array. The/lift drag ratio with and without cells attached is shown in Fig. 8.

The expected climb scenarios for November 4 and June 21 flight dates are shown in Fig. 9. Notice that on June 21 the vehicle should reach 60,000 ft 9 h after takeoff and remain airborne 19.5 h, but that on November 4 it can reach only 25,000 ft. This reduction in climb rate also makes winter flights more susceptible to occasional obscuration by clouds.

The First Solar Flights

The first solar flight of Sunrise I took place on November 4, 1974, at Bicycle Lake, CA. Sunrise I was launched at 10:00 a.m. and climbed to about 300-ft altitude, circled about 20 min, then landed. During the circling flight, it was evident that the heading had a decided influence on the rate of climb. During the summer months this effect is minimized; but late in the year, with the low sun angle, the 14-deg inclination of the wing upper surface during flight increases the power substantially when flying from the sun and makes flight into the sun essen-

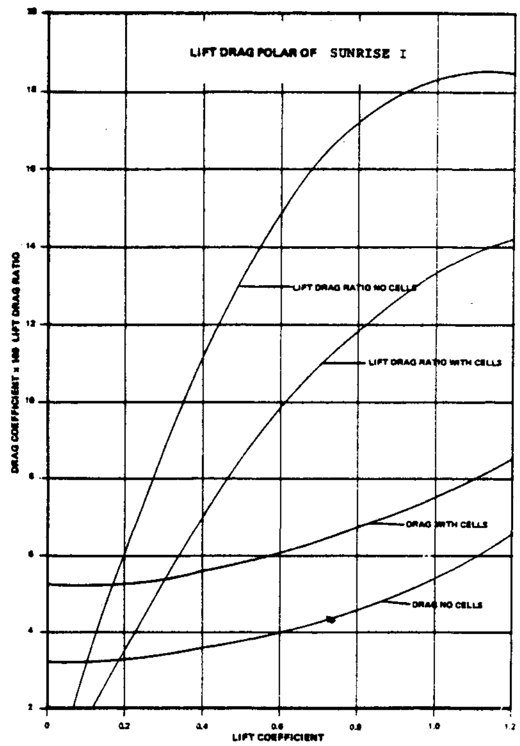

Fig. 8 Lift-drag polar of Sunrise I.

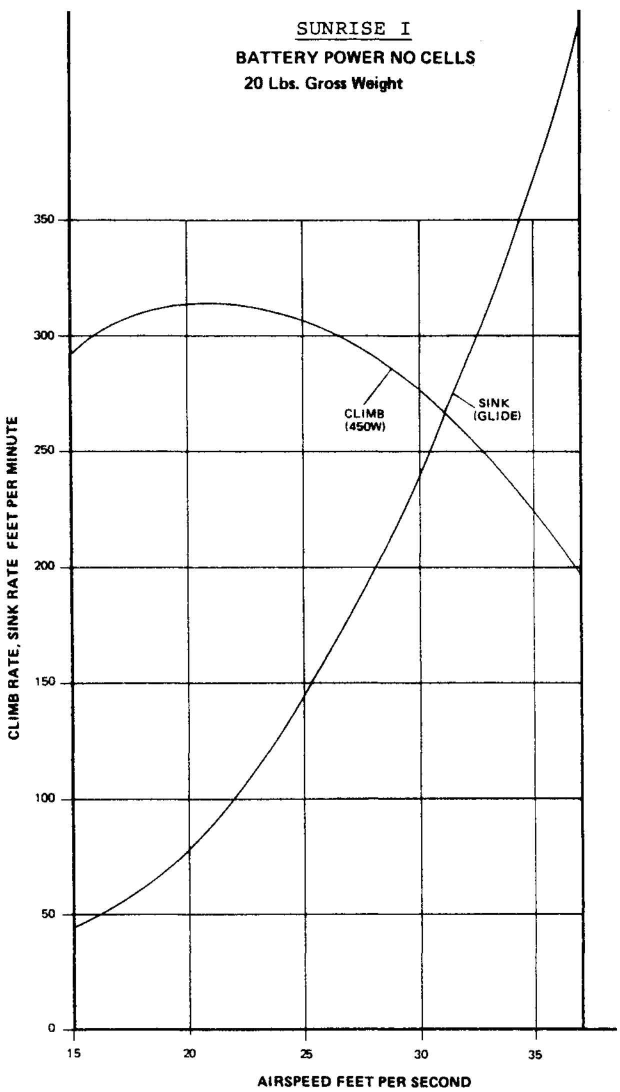

Fig. 7 Performance of Sunrise I on battery power.

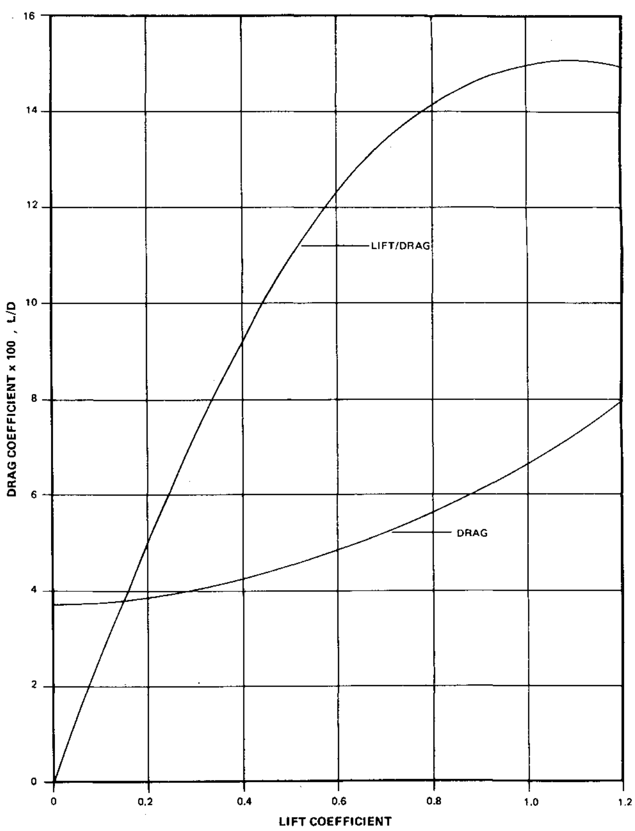

Fig. 9 Lift-drag polar of Sunrise II.

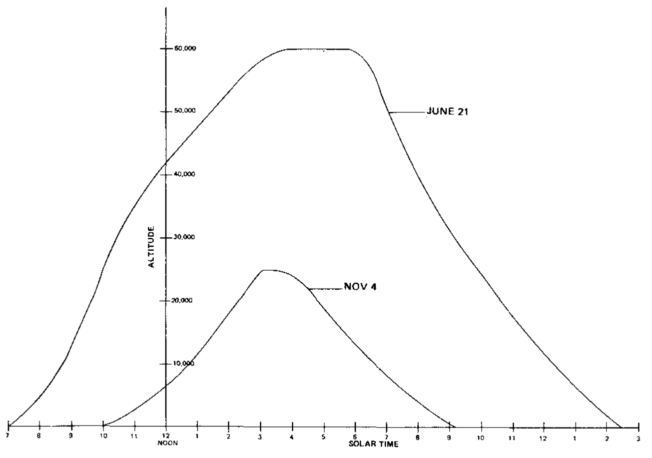

Fig. 10 Expected climb performance of Sunrise I.

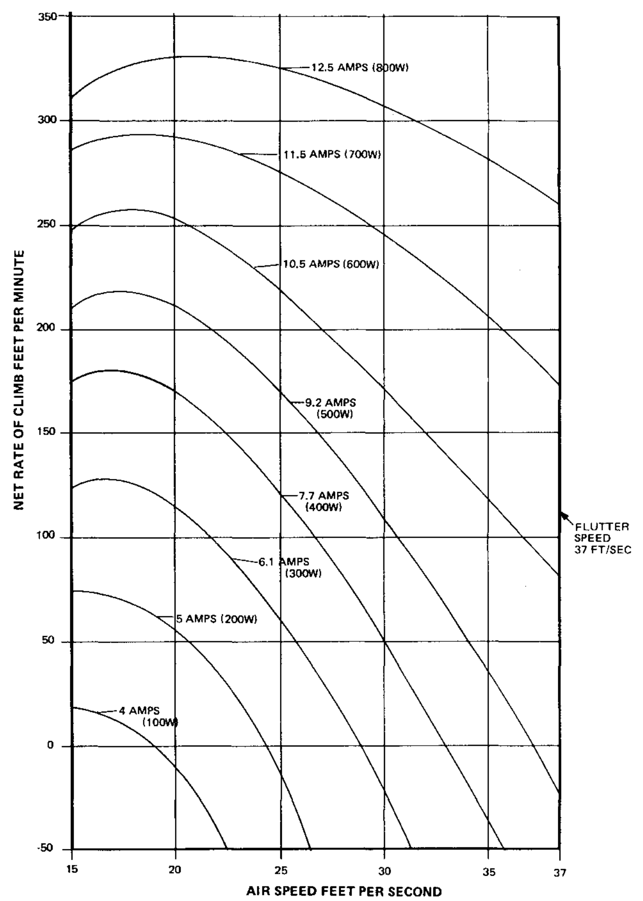

Fig. 11 Climb performance of Sunrise II.

tially unpowered. Because of this effect, and range restrictions, wind direction becomes very important.

One flight to 3000 ft was achieved by heading downsun and downwind for about three miles before attempting circling flight. This was accomplished by mounting the control station in a truck and chasing the vehicle across the desert. The altitude was limited by a buildup of cumulus clouds, which shadowed the vehicle. In early spring the vehicle was destroyed by severe turbulence at an altitude of about 3000 ft.

Measured Aircraft Polar of Sunrise II

The lift and drag coefficients of Astro Flight's Sunrise II are shown in Fig. 10. These coefficients were calculated from a number of performance measurements and glide tests using the simplified equation

$$C_d = C_0 + C_1^2/\pi A$$

This vehicle was constructed using a new solar array which necessitated increasing the wing chord at the root to 36 in. The solar array was at first affixed uniformly and smoothly to the upper wing surface with minimum increase in surface crag. However, by the time the high-altitude flight was attempted, the array had buckled due to wing flex and was no longer very smooth. It was estimated—and flight data confirmed—that, in this final configuration, drag was increased about 20% to the value shown in Fig. 10.

Figure 11 shows the sea level climb rate vs airspeed for various motor current and power levels. These climb rates would increase with altitude as a function of the reciprocal square root of air density holding motor current and indicated airspeed constant. Since the solar array had a maximum current capability of 15 and 7.5 A in the low- and high-altitude switching configurations, the expected sea level climb rates should have been 380 and 150 ft/min, respectively. However, the array voltage, even with 15 V of battery boost, would only allow a maximum current of 8 A to flow. This restriction reduced the maximum rate of climb with the sun in the most favorable position to 180 ft/min.

During the circling flight required by range restrictions, the average current during battery boost condition was measured to be 7 A. This agrees reasonably well with the rate of climb observed during this period, which was 120 to 150 ft/min. Loss of ac power to the ground station approximately 50 min into the flight caused premature jettison of the booster battery. This necessitated switching to the high-altitude configuration prematurely at low altitude rather than at 20,000 ft as planned. The climb rate at the resulting 5.5-A drive would then be 90 ft/min at sea level and 110 ft/min at 12,000 ft. This agrees closely with observed data.

The High-Altitude Flight of September 27, 1975

On the morning of September 27, 1975, Sunrise II was readied for its final high-altitude flight. Because of previous difficulties and logistics problems, a small pinion gear and small propeller were installed. The test plan called for takeoff between 9:00 and 9:30 a.m.; circling flight and climb to 46,000 ft by 4:30 p.m. The sky was clear and the wind calm. It was a perfect day for the attempt; and, even at 25,000 to 40,000 ft, where a jet stream had been active earlier, the winds were only 10 mph. The crew was assembled at 6:30 a.m.; and the vehicle and its support ground station were transported to the lake bed at Nellis Range 63. The vehicle and ground equipment were assembled and checked out by 8:00 a.m. Although the vehicle possesses a low positive climb rate with 5-A array current, it was decided to wait until 8-A array current was available. This required a hold until 9:30 a.m. in accordance with the test plan. At 9:18 a.m., subsystems were turned on and checked again; the bungee launch line was stretched and attached to the vehicle.

Launch took place at 9:35 a.m. The first 14 min were used in circling flight with a shallow climb. The effect of right and left extreme rudder trim was noted. Although spirally stable in all trim conditions, the yaw control was very sluggish, and the heading wandered continuously at minimum speed trim setting. At $T=0{:}14$, the power was shut down and 6 min of power-off stall tests were performed. These tests indicated that almost full-back stick was required to stall the vehicle and that stick-free recovery was normal with only a few oscillations in pitch. Indicated stall speed varied from 12 to 17 ft/s. This is consistent with calculations that indicated 15-ft/s stall speed. Because of the wandering in yaw at slower speeds, the vehicle was trimmed for 22- to 25-ft/s flight, the power turned on, and the climb resumed at $T=0{:}20$.

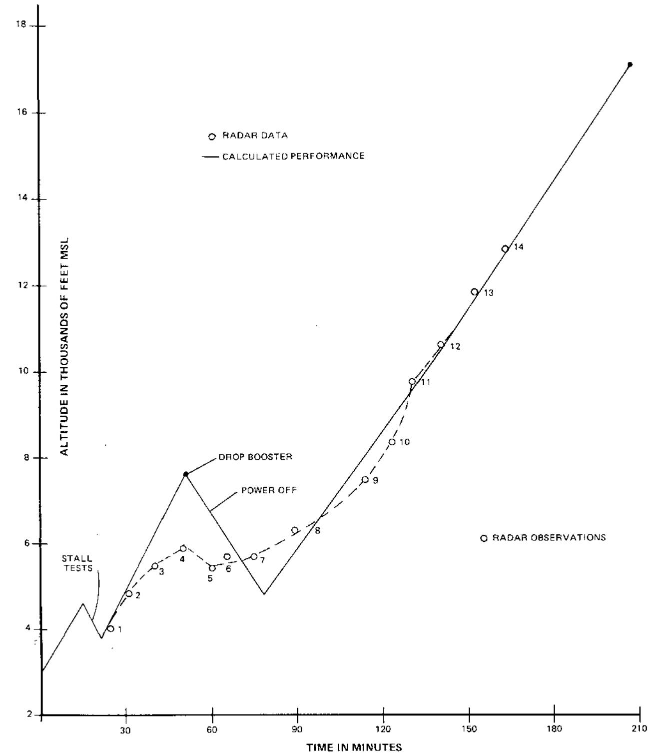

Fig. 12 High-altitude flight of September 27.

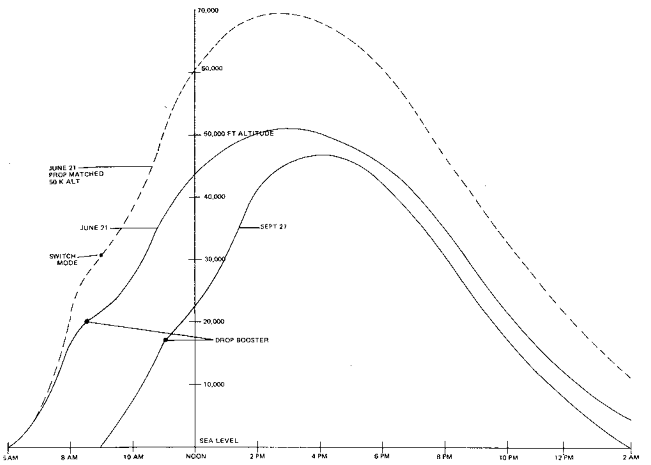

Fig. 13 Expected vertical flight profile of Sunrise II.

Sunrise II was flown on a 5-mile rectangular course on instruments using the sun sensor for direction and airspeed as the pitch indication. The power subsystem delivered only 8 to 9 A, indicating that the lithium battery boost voltage was inadequate to extract full performance with the small propeller. With a change of 25 V boost instead of 15 V used, the climb rate power could have been almost doubled since the solar array on the down-sun leg was capable of delivering 12 A.

The climb was uneventful until $T=0{:}55$, when all ac power was suddenly lost to the ground station. The battery-powered ac inverter system had run down. When this happened, extraneous signals from the ground station commanded jettison of the booster battery and commanded the vehicle into a spiral dive. The battery jettison was reported via radio link from the telescope tracking station. The vehicle was then at approximately 6000-ft altitude and 5 miles south of the control station over mountains of about the same altitude. For the next 17 min, while the ac power system was being repaired, no data on the vehicle condition or attitude were available. At $T=1{:}12$, power was restored. Telemetry indicated that the vehicle was in a left oscillating spiral dive and propulsion power was off. Vehicle rotation was stopped, airspeed stabilized, and power switched to the series, or high-altitude, mode since without the battery the low-altitude mode was inoperative.

It is estimated that at this time the vehicle had descended to about 4800-ft altitude and was out of sight below the mountain peaks. Using the last known position, a desired heading in sun coordinates was determined, and the vehicle was flown on this heading for 18 min when optical contact was reestablished. The vehicle was then nearly overhead at 6180-ft altitude. Climb was then resumed using the high-altitude power setting, and Sunrise flew a 5-mile rectangular path. Oriented along the prevailing sun line, the climb was uneventful for the next 2 h.

At $T=3{:}24$, the airspeed indicator was pinned off scale, indicating an airspeed in excess of 50 ft/s. This speed exceeded the flutter limit. When control was regained and the airspeed stabilized at 30 ft/s, the power was noted to be one-half of normal. This indicated that one of the solar arrays had failed, probably due to flutter during the high-speed dive. At this time the controller reported that the vehicle was again diving and not responsive to radio command. Within 10 to 15 s of this last dive, the tracking telescope reported aircraft breakup, which was confirmed by loss of telemetry. The nose section with one wing panel attached impacted about 6 min later. The rest of the vehicle was never found. Since the estimated altitude at breakup was 17,200 ft, and since the bare tail and wing tip surfaces had a surface loading of 1 oz/ft^2, it is estimated that these parts would require about 10 h to impact and would drift 50 miles downwind (Fig. 12).

The purpose of the high-altitude flight was to assess the ability of the vehicle to climb to high altitude on solar power, to be guided out of visual range on instruments, and to be navigated by the sun compass. All of these goals were achieved. The target altitude was not reached due to aircraft breakup, but the climb rate was established over 3-h time, indicating that design altitude of 46,000 ft would have been reached at about $T=7$ hr. Even the altitude reached has not yet been exceeded by a solar-powered aircraft.

Sunrise II was also destroyed by aerodynamic loads. During its flights it experienced airspeeds of 45 ft/s and even 50 ft/s a few times because of command and control problems. Since the allowable speed regime of these vehicles provided a 2.7-to-1 speed range, this would have been adequate under normal conditions.

The Expected Vertical Flight Profiles

The expected vertical flight profiles for the September 27 flight and for the planned June 21 flight are shown in Fig. 13. Because of the failure of the belt drive and the subsequent substitution of a pinion gear smaller than desired, the vehicle was limited by array voltage, rather than solar flux, to an altitude of 46,000 ft. The effect of flying late in the year with a low sun angle and the effect of circling flight, rather than using best sun angle because of range restriction, is shown. If flown on the longest day (June 21), the vehicle was capable of launch at 6:00 a.m. solar time and of reaching operational altitude of 52,000 ft at noon. Descent would begin at 4:00 p.m. Because of this late time in the day, the vehicle would then begin its descent in fading sunlight and would be expected to touch down at 2:00 a.m. the following day.

Conclusions

During the flight demonstration of the Sunrise airplane, many specific objectives were satisfied, among them—the ability

1) To build a complete airframe weighing 2 oz/ft^2 of wing area and an all-up weight of 4 oz/ft^2.

2) To assemble large arrays of solar cells having a specific power greater than 100 W/lb.

3) To convert electric power to thrust horsepower with a propulsion system including motor, gears, and propeller weighing about 3 lb/hp.
4) To achieve sink rates during glide of 1 ft/s.
5) To climb to high altitudes on solar power.
6) To navigate with a sun compass.

These are no small achievements for the world's first solar-powered aircraft.

Acknowledgments

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References

[1]Boucher, R.J., "Project Sunrise," AIAA Paper 79-1264, June 1979.

[2]Boucher, R.A. and Boucher, R.J., "Remotely Controlled Electric Airplane," U.S. Patent 3957230, filed July 30, 1973, issued May 18, 1976.

[3]Boucher, R.J., "History of Solar Flight," AIAA Paper 84-1429, June 1984.

[4]Boucher, R.J., "The Quiet Revolution," Published by Astro Flight Inc., Marina del Rey, CA, 1979.

[5]Boucher, R.A., "Electrics Made Easy," *Model Builder Magazine,* July 1973, pp. 42-43.

[6]Boucher, R.J., "The Gossamer Penguin Makes Historic Solar Flight," *RCM Magazine,* July 1980.

[7]MacCready, P.B., Lissaman, P.B.S., Morgan, W.R., and Burke, J.D., "Sun Powered Aircraft Designs," *Journal of Aircraft,* Vol. 20, June 1983, pp. 487-493.

[8]"OSTIVE Airworthiness Requirements for Sailplanes."

[9]Irving, F.G. and Morgan, D., "The Feasibility of an Aircraft Powered by Solar Energy," AIAA Paper 74-1042, Sept. 1974.