History of Solar Flight

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Abstract

This paper discusses the seven solar powered aircraft flown to date (1984). The Characteristics of these airplanes are reviewed and the prospects for future advancements in solar flight are addressed.

Introduction

Electric Propulsion of flight vehicles is not new. The earliest recorded success was the electric powered dirigible. La France, built by the two French engineers, Renard and Krebs in the year 1884. In that year it won the 10 Km dirigible race around Villacoulbay and Medon. The hydrogen filled La France measured 170 feet in length and was powered by a nine Horsepower electric motor. It was capable of speeds as high as 12 miles per hour. In 1814 the electric motor and battery was superior to its only rival the steam engine. Then along came the internal combustion engine and its miracle fuel, Gasoline. Work on electric propulsion for air vehicles was abandoned and the field lay dormant for almost a century. In 1957 Colonel Taiplan of the United Kingdom flew a Radio Controlled Model powered by a permanent magnet DC motor and a silver zinc battery, but these experiments were not continued. In the early 1960's Fred Militky of Kerkheim Tech, West Germany began to experiment with very lightweight free flight models powered by toy motors and one shot saline batteries. These models flew but were not considered successful. In 1790 my brother Roland and I at Astro Flight in Los Angeles California began our experiments with electric flight. From the very first we concentrated on achieving sufficient power to produce a practical replacement for the internal combustion engines used in radio controlled model airplanes and small drone aircraft. By 1972 we had developed models that could rise from the ground under their own power and with a little coaxing could perform simple aerobatic maneuvers such as loops and rolls. That same year we demonstrated our first Drone prototype to ARPA Colonel H, Federin. Our prototype used a single Astro 25 Ferrite motor and a Silver Zinc battery and established three world records for electric powered models, Distance 19 miles, Flight Duration 29.5 minutes and Average speed 55 miles per hour. Shortly thereafter Astro Flight was awarded a contact by the Northrop Aircraft Corporation to build an electric powered drone to carry their six pound surveillance payload. The author designed and built the Astro Model 7212 electric powered battlefield surveillance drone and began flight testing. In the summer of 1973 Astro Model 7212 demonstrated is ability to carry a six pound pay load for 1 hour and 20 minutes at an average speed of 75 miles per hour. Model 7212 was powered by three Astro 40 Ferrite motors and a bank of Eagle Pitcher Monoblock silver zinc batteries. Although limited in speed and range when compared to its gasoline powered competition, model 7212 possessed the attributes of being cool, clean, vibration free, and almost completely silent. It provided a stable platform for optical surveillance systems with no thermal or audible signature. In fact the vehicle was completely inaudible at altitudes over 300 feet. In one particular test of a smaller radio controlled electric powered vehicle we flew at altitudes of 500 feet over Will Rogers's home at the Historical Monument in Pacific Palisades, California. We had an observer from the Defense Department report to the then Assistant for DDRE , the honorable John Foster, that we could fly undetected over this monument as scores of unsuspecting tourists wandered in and around the house. ARPA showed little enthusiasm for either Astro Flight or their "crazy" idea for an electric powered air surveillance vehicle. Then we received the news that our friend and fellow electric flight enthusiast, Fred Militky, had converted had converted a Krahe Motor Glider to electric power. Fred reported that he had achieved the words first piloted electric flight of 25 minutes duration at Linz, Austria in the HB-3 conversion built by H.W. Brditschka OHG of Haid bie Linz. Fred removed the 26 horsepower gasoline engine normally installed in the Krahe and substituted a 13 horsepower Bosch aircraft starter motor and a bank of Varta NiCad aircraft starter batteries. It was reported that a maximum altitude of 1,500 feet was reached during the 25 minute flight. Remember, the Krahe motor glider was not specially designed for electric flight.

In the mean time interest at ARPA was increasing and they initiated a few studies with Batelle, Melpar and R and D Associates. These guys were downright pessimistic and concluded that no battery would ever possess the energy density of gasoline!!! Such conclusions were, of course, obvious even to the most untutored eye. John Foster was more reasonable and suggested that if we could figure out a way to increase our flight times to twelve or more hours we might have a sale. Our Nicad battery powered models could fly comfortably for fifteen minutes and with careful energy management for about thirty minutes on the 1200 mahr Sub C Nicad cells then available that had an energy density of only 12 watt-hours per pound. By using silver zinc batteries in our Astro Model 7212 UAV we had demonstrated flights of one hour 20 minutes while carrying a six pound payload or 25% of air vehicle gross weight. We experimented with one shot Lithium D cells built by Power Conversion of New York in a lightweight Radio Controlled model and demonstrated flights over three hours with no payload. For twelve hour flights we needed a breakthrough. Heliotek in Sylmar California had developed a new high efficiency light weight solar cell for the Hughes Space Satellites with a power density of 100 watts per pound and a solar efficiency of 14 percent. Since this power density was comparable to the Nicads we were using in our previously successful electric powered models we knew that an airplane powered only by solar cells would fly. This was a trivial problem. But if somehow we could store enough of the sun's energy during the day, we could then use that energy to continue flying all through the night we could theoretically fly forever. But no suitable battery was available. My brother Roland came up with the following scheme. Store the energy in the Earth's gravitational field!!! If we could build an airplane that could climb high enough during the day to be able to glide all through the night and still be at some reasonable altitude say a 30,000 feet at dawn we would have created perpetual flight. It all looked feasible. It would be difficult but with careful attention to detail it could succeed. We filed our patents and submitted our proposals to our prospective customer Kent Kressa of ARPA. We called our invention **Sunrise**.

Project Sunrise

Our proposal to ARPA was to build a 100 foot wing span vehicle to carry the 50 pound tactical payload envisioned by the customer. ARPA counter offered to pay for a paper study to prove feasibility. Contractual discussions which began in early 1971 finally resulted in a flight demonstration contract in April 1974. Astro Flight would build a 1/3 scale model of Sunrise, fly it on a government test range and share the flight test data with ARPA. We had expected to receive our contract in January so that we might make our initial flight tests in the summer months when the sun is highest in the sky and the days are longest. With the late starting date we had to work many long days from 7AM to midnight to get Sunrise I ready for flight a few days after Labor Day. Astro Flight Model 7404-1 (**Sunrise**) made its first test flight under battery power on September 17, 1974. Shake down flights showed that the propulsion system and the command and control systems were OK and that Sunrise I had an excess power ratio of seven. That meant that Sunrise I could maintain level flight on one seventh of its maximum power. It could maintain altitude on 85 watts. Sunrise I had a wing span of 32 feet and weighed 19 pounds. At this weight and with this power level we calculated its service ceiling at 75,000 feet. Heliotek delivered the solar panels but they were over weight and under powered. The panels weighed 6.5 pounds instead of the promised 4.5 pounds and the power output was only 450 watts instead of the 600 watts promised. To make maters worse the overweight solar panels mounted on the upper surface of the wings were behind the center of gravity, so we had to add two pounds of lead ballast to the motor compartment to rebalance the airplane. Sunrise I now weighed 27 ½ pounds ready to fly with lead ballast, Telemetry down link and radar beacon. We recalculated the probable service ceiling to be 25,000 feet in June and 10,000 feet in December. It was by now late in October and the rainy season in California had begun. A very wet and windy winter was forecast that year. We argued with ARPA that the prudent course would be to put the solar flight tests on hold until late spring of 1975 or to move the flight tests to Australia. We were instructed to fly at the earliest possible date at Camp Irwin, California. At 10:00 AM in the morning of November 4, 1974 Sunrise I rose slowly and silently from the dry lake bed at Camp Irwin. It was powered entirely by the 4,096 solar cells on its wings. The age of Solar Flight had arrived. Flight test measurements indicated that the profile round solar cells on the upper wing surface had almost doubled the profile drag of the Eppler 387 airfoil. This was aggravated by the fact that the 2-1/4 inch round cells would not stay stuck down to the curved upper surface of the wing. The probable service ceiling in November was now closer to 5,000 feet. Scores of solar flights of three and four hour's duration were made that wet and windy winter. Some flights were made in winds of 20 to 25 miles per hour!! It must be remembered that the wing loading of Sunrise I was only four ounces per square foot and so it's stall speed was only 12 miles per hour. This is analogous to flying a Cessna 150 in 60 miles per hour surface winds. Sunrise I was seriously damaged when caught flying in a sandstorm. ARPA was sufficiently encouraged to authorize construction of an improved version Sunrise II. We received a contract on June 10, 1975 to proceed building Sunrise II. We worked 16 hour days all that summer. A new digital telemetry system was built and tested and single new samarium cobalt Astro 40 motor replaced the two Astro 40 ferrite motors used on Sunrise I. Heliotek was now owned by Hughes Aircraft and now had a new name, Spectrolab. Bob Oliver and the guys at Spectrolab had developed a new high efficiency solar cell that measured 2 x 4 cm by 8 mm thick and delivered 14 percent efficiency. Our new solar panel weighed 4 ½ pounds and delivered a full 600 watts. This was much better than the original 100 watts per pound that was originally promised. Sunrise II made its maiden solar power on a dry lake at Mercury Nevada that was controlled by Nellis AFB on September 12, 1975, just three months and two days after contract award! Flight tests indicated that Sunrise II should have a service ceiling of 75,000 feet in summer and 25,000 feet in winter at the 30 degrees north latitude of the test range. At this latitude 24 hour flights would be possible during the months of May, June and July. After many months of flight testing Sunrise II was damaged after a failure in the command and control system that caused an airframe structural failure.

These specific objectives were satisfied during the flight demonstration program.

1. The ability of flying heavier than air fixed wing aircraft on solar power alone.
2. The ability of climbing to extreme altitudes on solar power alone.
3. The feasibility of making long endurance flights at equatorial latitudes and long summer flights at temperate latitudes was established.
4. The ability of building large lightweight airframes weighing less than two ounces per square foot was demonstrated.
5. The ability of assembling large solar arrays having a specific power of greater than 100 watts per pound was demonstrated.
6. The ability of building a high efficiency Samarium Cobalt Motor weighing less than 1 ½ pounds per horsepower was demonstrated.

The Aerodynamic Configuration

The aerodynamic configuration of Sunrise is shown in fig 1. Sunrise is a conventional high wing monoplane driven by a fixed pitch tractor propeller. No ailerons are used, rather the design utilizes a six degree dihedral coupled to a large aerodynamically balanced rudder to provide roll / yaw control. Pitch control is affected by a very small elevator attached to a large horizontal stabilizer. The landing gear uses a single main wheel with a wire tail skid and wire outrigger wires on each wing. Take off is assisted by a 50 meter length of stretched bungee cord used as a catapult and fitted with a drop away hook. The motor was started after the tow line had dropped away. Sunrise II had a stall speed of 14 feet per second and a cruise speed of 35 feet per second at sea level. The climb rate varied between 100 and 400 feet per minute depending on sun angle on the solar array. At altitude the cruise speed would increase to 100 feet per second. The sink rate during the gliding mode was measured to be less than 1 foot per second

Sunrise II General Characteristics

Gross Weight	22.5 pounds
Wing Span	32 feet
Wing Area	90 square feet
Aspect Ratio	11.4
Airfoil	Eppler 387
Wing Loading	0.25 lb. / sq. ft
Length	14.4 feet
Propeller	30 in dia. x 16 in. pitch
Motor	Astro Cobalt 40
Solar Array	4,480 cells
Cell Size	2 x 4 cm
Array Power	580 watts
Stall Speed at sea level	14 feet per second
Cruise Speed at sea level	35 feet per second
Cruise Speed at 60,000 feet	81 feet per second
Maximum Altitude	75,000 feet

Sunrise II Airframe Structure

Sunrise I and II were constructed almost entirely of wood using the same construction techniques used in international free flight competitions such as Wakefield and FAI Nordic events. The craftsmen who built the sunrise vehicles were all internationally known competitors from Southern California: they included Robert Boucher, Roland Boucher, Phil Bernhardt, David Hauler, Bill Warner and Jim Oddino. The wing used a box spar with spruce caps and balsa webs to take the bending loads and a balsa sheeted D tube to absorb the torsion and drag loads. The outer wing panels were removable and were secured by a single ¼ inch steel bolt. The wing center section was also attached to the fuselage with a single ¼ inch steel bolt.

The bare wing structure weighed 2.3 kg but was stressed to handle a 5.3 G aerodynamic load as per OSTIV sailplane specifications. The fuselage used a warren truss made up of 3/16 x 3/16 Douglas fir longerons. Ash blocks were used to absorb all single point loads such as the wing attachment points, landing gear attachment and tail attachment. The entire frame work was covered with ½ mill DuPont Mylar sheet. The Mylar sheet was attached to the frame with 3M industrial adhesive and then shrunk tight by the application of heat. Torsion tests revealed that the wing stiffness increased by 50% after covering. The 180 square feet of Mylar sheet on the upper and lower surfaces added 1.3Kg to the wing raising its weight to 3.5 Kg. The fuselage of Sunrise II was 14 feet long and 1 ½ feet deep yet it weighed only 0.83Kg or 29 ounces. The original Sunrise I fuselage was built with hard balsa instead of Douglas Fir and weighed only 14 ounces but it suffered structural failure on the first hard landing so its longerons were reinforced with spruce doublers.

The Solar Array

The solar power subsystem on Sunrise II consisted of four sub arrays of containing 1,120 Spectrolab 2 x 4 cm high efficiency solar cells. The sub arrays were wired in series parallel so that each sub array delivered 3.8 amps at 37 volts, sun normal air mass zero. The sub arrays were attached to a one half mil Mylar substrate that was in turn attached to the wind structure with industrial adhesive. The electrical circuit was arranged to deliver 15 amps at 37 volts or 7.5 amps at 74 volts. In actual tests the panel delivered slightly more power and could deliver 580 watts. The bare cells weighed a total of 4.5 pounds, but with all cables connectors and switches the solar power subsystem weighed 5.5 pounds. At this weight the specific power was 105 watts per pound.

Weight Summary for Sunrise II

Wing	3.496 grams	
Fuselage	834 grams	
Horizontal Stabilizer	408 grams	
Vertical Stabilizer	213 grams	
	Airframe Subtotal	4,951 grams
Astro 40 Cobalt Motor	453 grams	
Speed Reducer	359 grams	
Propeller	142 grams	
	Propulsion Subtotal	954 grams
Solar array		2.523 grams
Command Receiver	200 grams	
Servo Actuators (8)	270 grams	
Flight Sensors	176 grams	
Encoder	149 grams	
Telemetry Transmitter	83 grams	
Lithium Battery	494 grams	
	C and C Subtotal	1,372 grams
X-Band Beacon		586 grams
Gross Weight		103,086 grams

Summary

I believe that the historic flight of Sunrise I on November 4. 1974, the world's first solar powered aircraft will prove to be a key event in aviation history. During this first decade of the solar age we have seen real progress in making airplanes more energy efficient. I would like to thank John Foster and Kent Kressa for making this exciting project possible.

Larry Mauro's Solar Riser

Larry Mauro, the president of Ultralight Flying Machines of Santa Clara, California, built a solar powered version of his Easy Riser hang glider. The Easy Riser is a swept wing, tail less biplane. It had been flow both as a hang glider and as a gasoline powered ultralight. The solar adaptation consisted of installing a 3 ½ horsepower Bosch Starter Motor and a 30 volt Nicad battery pack, and a 350 watt solar panel. The solar panel did not have enough power to fly the Solar Riser; rather the solar panel was used to charge the Nicad battery. In bright sun the solar panel could charge the Nicad battery in about three hours. Once fully charge the battery could power the motor for about 10 minutes. The 3 ½ horse power Bosch motor was coupled to the 41 inch diameter propeller with timing belt and a pair of pulleys. It must be remembered that the Solar Riser was neither designed for solar flight nor for electric power so its performance was a bit marginal. The longest recorded flight covered about half a mile at altitudes varying between 5 and 15 feet. Larry made his first flight on April 20, 1979 at Flabob Airport in Riverside, California. Larry has flown the Solar Riser a number of times since and demonstrated it at the EAA Fly in at Oshkosh, Wisconsin. It is now on display at the EAA Museum at Hales Corners, Wisconsin.

Solar Riser Characteristics

Wing Span	30 feet
Empty Weight	123 pounds
Gross Weight	275 pounds
Nicad Battery	30 Volts
Battery Capacity	15 amp hours
Solar Array	36 volts
Array Capacity	10 amps
Electric Motor	31/2 Horse Power
Propeller Diameter	41 inches

Freddie To and his Solar One

Two months after Larry Mauro's first flight of the Solar Riser, the team of Freddie To, Ken Steward, and David Williams launched their Solar One on its maiden flight. Solar One is a conventional shoulder wing monoplane. It is rather large and heavy, having a wing span of 68 feet a length of 22 feet and weighing 220 pounds empty! The airframe is built of spruce and balsa and covered with Solar Film, a thin polyvinyl sheet material. Freddie To is an architect in London and is a member of the Kramer Committee, the group that made up the rules for the famous Kramer Competitions. Freddie originally built the Solar One as a pedal powered airplane to attempt the Channel crossing. The airplane proved to be too heavy to be successfully powered by human power and was then converted to solar power. The maiden flight of Solar One took place at Lasham Airfield; Hampshire on June 13, 1979, one day after Brian Allen had successfully pedaled the Gossamer Albatross across the English Channel from Ramsgate to Cape Gris Nez to capture the Kramer Prize for the MacCready Team. The First Flight of Solar One was piloted by Ken Steward who reports that speeds of 35 knots and altitudes of 80 feet were attained. The aircraft was essentially powered by the 30 volt 25 ampere hour Nicad battery pack. The solar array could recharge the battery in about 1 ½ hours so several flights were made that day. Freddie had hoped to try a channel crossing with Solar One but its performance was not encouraging enough to warrant the attempt. Solar One now resides in the London Museum. Freddie reports that the design can accommodate covering the entire upper surface of the wing with solar cells. If this were done and if high efficiency cells like those used on Sunrise II were used it is probable that Solar One could fly on solar power alone without the help of batteries. Alas Freddie could not afford to purchase enough of these cells to do the job right. The exorbitant price of high quality solar cells has been limiting the development of many practical applications for solar power.

The Solar Propulsion System on Solar One.

The solar array on Solar One consisted of 750 each 3 inch diameter Solarex solar cells arranged in two arrays. Each array could deliver 12 amperes at 36 volts in full sunlight. Together both arrays could charge the Nicad battery in 1 ½ hours. The Nicad battery pack consisted of 24 cells of 25 amp hour capacity connected in series. The battery pack weighed 65 pounds. Four Bosch one horse power permanent magnet DC motors were coupled to a single five foot propeller by means of a bicycle chain and sprockets with a three to one reduction ratio. The motors spin at 3,300 Rpm and the propeller at 1,100 Rpm. At full power the four motors absorb draw about 150 amperes from the battery so that the four kW of power lasts about 10 minutes, Freddie reports that Solar One can climb for about 8 minute and then maintain zero sink for about two minutes more.

Solar One Characteristic

Wing Span	68 feet
Length	22 feet
Wing Area	260 square feet
Airfoil	Wortman FX180
Aspect Ratio	17.8 to 1
Propeller Diameter	63 inches
Solar Array	750 solar cells
Cell Size	3 inch diameter
Array Current	12 amps each
Array Voltage	36 Volts
Number of Motors	4 motors
Motor Type	Bosch 1 Hp
Transmission ratio	3 to 1 step down
Transmission Type	Bicycle Chain and Sprocket

The Gossamer Penguin

On May 28, 1980 the Gossamer Penguin made is first solar powered flight with young Marshall MacCready at the controls. I believe that this was the world's first piloted solar powered aircraft. Like Sunrise I and II it used no batteries and flew on solar power alone. The Gossamer Penguin was initially built as a back up for the Gossamer Albatross that was successfully pedaled across the English Channel by Brian Allen. After this historic flight Paul MacCready and the Gossamer Crew flew back to California with three airplanes, the historic Albatross I, a backup Albatross II and the Smaller Gossamer Penguin. Shortly after his return to California Paul, was asked by Dale Reed at NASA Dryden to run a flight test program with the Albatross II. The Albatross I was being sent to the London Museum of Science and Industry. NASA wanted to measure the Lift Drag ratio of the Albatross and wanted to power it with an electric motor to eliminate any power variation from the human pilot and because of the ease of measuring motor power. I soon had the job of building an electric propulsion system for the Albatross. I used two Astro 25 Super ferrite motors and a three stage timing belt reduction drive to turn the 11 foot prop. The reduction ration was 125 to 1, the motors turned 12,500 Rpm and the propeller turned 100 rpm. I used a battery pack made up of 32 GE 1200 mahr Nicads. The whole system produced ¾ HP and weighed 7 pounds.

Paul MacCready came to our shop to pick up the motors and batteries and since he is an old time modeler, naturally he wanted to take a tour of our shop. I showed him the damaged wing panels of Sunrise I and Sunrise II with the thousands of tiny solar cells still attached. He immediately asked if there was enough power in the solar panels to fly the albatross. A few calculations indicated that there was not quite enough power for that job. We needed a smaller airplane and a lighter pilot. Brian Allen the Albatross pilot weighed 140 pounds. Paul said that he had just the right combination, the smaller Gossamer Penguin and his 12 year old Marshall who had flight experience as an Albatross pilot. I agreed to lend our Astro Sunrise II solar panel to the Gossamer Penguin project if the Sponsor DuPont would be willing to cover the expense of repairing the damaged panels. A few weeks later we were in business. Ray Morgan, an aeronautical engineer at Lockheed California joined the MacCready team as Program Manager and rented an empty industrial building near the airport in Simi California to erect the Penguin. Ray had the help of the seasoned Albatross veterans who were experienced modelers and skilled craftsmen, men like Dave Saks, Blaine Rawdon, Ted Ancona, Bill Watson, Martin Cowley, Mike Bame, Steve Miller and Bobby Curtin. They soon had the Penguin erected and ready for its first flights on battery power. I chose our Astro 40 Super Ferrite motor and a battery made up of 26 Sub C Nicads to power the Penguin. With this battery pack we had enough stored energy to fly the Penguin for about 15 minutes before having to recharge the battery. By using our Astro Model 112 quick charger we could recharge the battery pack in 15 minutes so there was very little waiting between flights. The Penguin used an 11 foot diameter Larrabee design propeller as did the Albatross. The propeller needed to turn at 120 to 130 Rpm to keep the Penguin aloft. Our Astro 40 Super Ferrite Motor likes to run at 12,000 to 15,000 Rpm for best power and efficiency, so Jim Watkinson, the shop foreman at Astro Flight fabricated a speed reducer using two timing belts and a bicycle chain. The two belt reduction stages were 5 to 1 and the chain stage 5.12 to 1 for a total reduction ratio of 128 to 1. Early flight tests on battery power indicated that about 350 watts of electric power were required to fly Penguin with 95 pound pilot Marshall MacCready aboard. This was a serious problem since we had only 250 watts from the repaired Sunrise II solar array. Originally the Sunrise II solar array delivered 580 watts but that was at high altitude with air mass zero. We were trying to fly at sea level. Because of the damage to the array on the last flight of Sunrise II we had only 2/3 of the original power. Paul MacCready had estimated that 250 watts would be sufficient but flight tests confirmed that 350 watts would be needed. The Penguin was carefully reworked to remove all wrinkles in its Mylar covering, to fill all air gaps and to clean up the aircraft as much as practical. In the meantime Paul had found a source of more solar cells very much like those used on Sunrise II, they were called HS318 cells and Hughes Aircraft has 18,000 of these cells left over from a Satellite program. They were reject cells but still had excellent efficiency of over 12%. While not quite good enough for the government program they were just what we needed. Paul arranged for a load from the Air Force via NASA so we went over to Hughes and picked up the cells. We then fashioned a fourth solar panel for the penguin. We now had the 400 watts we wanted.

Just as things began to look good, disaster struck! Marshall was practicing a simulated solar flight at an altitude of about 15 feet when the Penguin was struck by a sudden gust of wind. The penguin did a quick snap roll to the left. Marshall jumped out through the side of the Penguin and landed on his feet on the runway, and then seventy feet of airplane collapsed on top of him. Luckily Marshall was only bruised and was up and walking around within a few minutes. At that point it all looked hopeless, but all the broken pieces were gathered up and brought back to Simi. The Mylar covering was stripped from the carcass and a damage assessment began. Just about every carbon graphite spar and tube was broken in at least one place. Bill Watson began repairing the spars with aluminum tubing and Kevlar splices while the rest of the crew began making new wing ribs, repairing the propeller, etc. Two weeks of around the clock effort paid off and Ray Morgan and his crew had the bird back together again. During this time my crew at Astro had finished work on the four solar panels and had them tested and ready for installation on the Penguin. By six PM on Saturday evening we had the Penguin erected and the solar array installed.

Early Sunday morning two battery powered flights were made to get the Penguin properly trimmed. Then the first flight on solar power was attempted. The power was too marginal but a quick inspection revealed that one or our electrical connections was broken and that we had been trying to fly on ¾ power. If we had elected to go back to the hangar for repairs it would have meant scratching that day for more solar flights. Shafter gets too windy after 10AM so we were running out of time. We decided to wait for another half hour for the sun to rise higher in the sky and then to try once more. Then I remembered that since this was to be a solar powered flight we had no need for the seven pound NiCad battery pack still installed but not being used. The battery was removed and Paul and Ray prepared the Penguin for is historic solar flight.

At 9 AM on May 18, 1980 the Gossamer Penguin was hand towed to an altitude of about two feet and then released. Young Pilot Marshall MacCready guided the Penguin straight down the runway while climbing to an altitude of about five feet. He held this altitude for a distance of about 500 feet before Paul asked him to land. The era of manned solar flight had arrived.

The DuPont Company, our sponsors for the Albatross and Penguin projects asked us to fly the Penguin one more time for the news media and this time with an adult pilot. Since the Penguin could only carry a 95 pound pilot, the search for a small experienced woman pilot was started. A few weeks later Janice Brown, a School teacher from nearby Bakersfield, California, and experienced commercial pilot and cute little lass weighing only 95 pounds joined the Gossamer Penguin team. With the cooperation of Dale Reed at NASA Dryden the Penguin was taken to a NASA hangar on Rosamond dry lake and prepared for another solar flight. With hundreds of TV and newspaper reporters a official witnesses Janice Brown flew the Penguin on a two mile long flight over the desert. The Gossamer Penguin was then retired from active life and now resides in a museum in Texas. The MacCready team now turned their efforts to building the Solar Challenger.

Gunter Rochelt and the Solair I

While the Solar Challenger team worked in California a competitor was hard at work in Munich, West Germany. Gunter Rochelt, an industrial designer in Munich, was building a solar powered canard. In contrast to the approach taken by the Challenger team, Gunter concentrated on making his aircraft as clean and aerodynamically efficient as possible. The entire structure was build with DuPont Kevlar. Solair I was a remarkable achievement not only because of the engineering and craftsmanship shown but also because Gunter and his wife built Solair I with their own hands and without any financial assistance. Solair I represented a couple of years of hard work. Gunter took Solair I to Biggin Hill airport about 60 miles from Manston RAF Base where we were with our Solar Challenger. Gunter was attempting a channel crossing at the same time that we were! We had heard some vague rumors about his airplane but we had no solid information. Then a few days after we got settled in at Manston we received a phone call from Gunter inviting us to come to Biggin Hill to see his airplane. Martin Cowley and I drove over to Biggin Hill that afternoon. Gunter was waiting for us with Champagne and Cognac to brighten our spirits and get us into the proper mood to witness the unveiling of his creation. The airplane was absolutely superb, the workmanship was flawless and Gunter had even installed a digital instrument panel. Solair I had a 53 foot wing span (about six feet longer than Challenger) but its gross weight was 200 Kg or about 100 pounds heavier than Challenger. Solair I had a little more than half the area of solar cells as Challenger. Gunter admitted that he did not have enough solar power to climb but had installed a fifty pound Nicad battery pack under the seat. The idea was to sit in the sun and charge the batteries, then when the batteries were full charged to take off and climb under combined solar and battery power. The after fifteen or twenty minutes when the batteries were run down he would continue to cruise at zero sink while looking for a thermal. Once in lift he could climb to a safe altitude while recharging the battery then head for France. It just might work, but luckily for us Gunter did not get any English sunshine either. He was still there in Biggin Hill waiting for the sun when Steve Ptacek landed at Manston; the race to be the first across was over. Gunter visited California last month and stopped by to visit with Paul, Ray and me. He reported that he has had flights as long as five hours with Solair I. He said that he hopes that someday someone will come up with a prize for the first solar flight across the USA. If that day comes Gunter will be ready.

The Solair I Aerodynamic Configuration

The Solair I is a canard monoplane with a pylon mounted wing and a pusher propeller. Full length flaps are fitted to both the canard and main wing. The propeller blades fold back for minimum drag in thermalling flight. Yaw control is achieved with pivoting wing tip plates not unlike the Icarus design of Taras Kacenik. The wing span is 16 meters or 53 feet and the total surface area is 22 square meters including the canard. The airfoil is the Wortman FX63-137. I estimated the Aspect ratio to be about 14. Gunter estimates that the minimum sink rate is 1.5 feet per second, which is very low. All in all the Solair I is a very clean design.

The Solair I Solar Array

Gunter chose to use Solarex cells that are 8.5 cm x 8.5 cm. They are semi octagon shaped, they are shaped more like a square with the corners cut off. With the Wortman airfoil and its high upper surface curvature it was not possible to have the solar cells conform to the airfoil shape. Gunter approximated the airfoil with a number of straight line segments then filled in the remaining space with clear silicone rubber. He reports that it took him and his wife three months to sand the silicone to a smooth aerodynamic shape. He then covered the silicone with a layer of1/2 mil Mylar. The result was a glass smooth finish, but Gunter estimates that the process added about 35 pounds to the airplane. Also after being installed in the wing the panels delivered only 1,800 watts instead of the 2,200 watts measured before covering. In spite of the better aerodynamics, I think that the addition of 35 pounds was a bad trade off.

The Solair I Propulsion System

The Solair I used two samarium cobalt motors especially built for Gunter by Karl Friedel. They are capable of handling 2.2 kW each. Gunter reports the motor efficiency was as high as 86%, very good indeed. The motors are coupled to the folding propeller by means of a two stage gear box with a step down ratio of 14 to 1. Since the propeller is said to spin at about 360 rpm, the motor speed must be about 5,000 Rpm.

Solair I Characteristics

Wing Span	16 meters
Surface Area	22 square meters
Aspect Ratio	14
Airfoil	Wortman FX 63-137
Length	5.4 meters
Empty Weight	120 kg.
Flying Weight	200 kg
Solar Array	2,499 cells
Solar Cell type	Solarex
Cell Size	8.5 x 8.5 Cm
Array Power	1,800 watts
Electric Motors	Karl Friedel
Magnet type	Samarium Cobalt
Motor Power	2.2 kW
Motor Efficiency	86 percent
Minimum Sink Rate	0.42 m / sec
Maximum Climb Rate	0.5 m / sec
Cruise Speed	40 km / hr
Glide Speed	26 km/hr

The DuPont Solar Challenger

The DuPont Company was sufficiently encouraged by the flight of the Gossamer Penguin to sponsor a much more ambitious program. The asked us if we could design and build a solar powered airplane that could cross the English Channel. We thought they would never ask!!! Paul MacCready assembled a group of veterans from the Albatross and Penguin programs at Henry Jax house in Santa Monica, California: Those there included Henry Jax, Peter Lissaman, Robert Boucher, Ray Morgan, Blaine Rawdon and Martin Cowley; the group established the general arrangement and functional requirements for the new channel crosser. It was to be called the Solar Challenger and Ray Morgan was made the program manager. Ray and his crew at Simi began the detail design and building of the Challenger. Peter Lissaman and his crew at Aerovironment Pasadena designed the flat topped airfoil for the wing and the aerodynamic design of the propeller. Robert Boucher at Astro designed the solar array, the electric motor, the speed reducer, the electrical control system and the power instrumentation system. Jim Watkinson and Margaret Jewett and the rest of the Astro crew built the solar electric propulsion system.

The Solar Challenger Aerodynamic Configuration

The Solar Challenger is a conventional high wing monoplane with a tractor propeller. The fuselage is rather deep and of the pod and boom arrangement with the boom extending forward to carry a very large propeller. The wing is cantilevered and has a 46 foot wing span, a five foot chord and a wing area of 235 square feet. The horizontal stabilizer is very large and squat having a span of 13 feet and chord of 8 feet. This unusual shape came about because of the large number of solar cells. When we tested the 18,000 cells at Astro Flight we mistakenly assumed that they would all be of the same 2 x 6 cm size at the first HS301 cells we had tested for the Penguin. As it happened about 12,000 cells were this size but we found a few cartons of slightly larger 2.2 x 6.5 cm cells. These were good cells but could not be mated with the smaller cells in the same array string. All cells in a given string had to be matched in output to obtain the maximum power. We made all the strings that we could with these larger cells, then we asked Ray where he could stick them. About the only place that made sense at that time was the horizontal stabilizer so instead of the original three foot chord, the chord was extended to eight feet. One thing was certain; the Solar Challenger would be very stable in pitch! Peter Lissaman was asked to invent an airfoil with minimal upper surface curvature so that we would have fewer problems attaching the flat solar cells the wing upper surface. This had been a problem on Sunrise I and Sunrise II. Peter invented an airfoil that was absolutely flat for 85% of the chord. A swept vertical stabilizer was mounted on the tail boom behind the horizontal stabilizer and fitted with a balanced rudder. The landing gear consisted of a sprung BMX bicycle wheel for the main gear, small auxiliary nose and tail wheels and wire skids on the wing tips. Although a bit unusual in appearance it possessed the elegant simplicity of good design.

The Solar Challenger Aircraft Structure

Both the Albatross and Penguin airframes used extensive wire bracing to keep the carbon fiber tubular spars in pure compression and to eliminate all bending and buckling loads. This wire bracing added much unwanted drag. The Solar Challenger was a full cantilevered design so the tubular spars had to carry both torsion and bending loads. The spars would be subjected to tension and shear stresses as well as compressive stresses. The tubular spars would have to be much stronger and somehow the side walls would have to be kept from buckling in order to load the carbon caps to their ultimate strength. An ingenious sandwich construction provided inherent structural stability and great strength while still being light weight. The fabrication technique consisted of spiral wrapping two or three layers prepregnated unidirectional carbon 0.005 inches thick at 45 degrees around a waxed aluminum mandrel and then adding linear caps both top and bottom and back and front. The whole assembly was then spiral wrapped with 0.001 inch thick polypropylene tape and then cooked in a long oven. The finished carbon tube was sanded ten wrapped with a ¼ inch layer of Nomex honeycomb that was bonded to the carbon tube with epoxy. Finally two layers of Kevlar cloth was wound around the Nomex and bonded with epoxy. By using this technique and other light weight materials Ray was able to build an entire airframe that weighted only 145 pounds.

The Challenger Solar Array

The solar array for the Solar Challenger used 16, 128 solar cells wired in sub arrays three cells wide by 72 cell long. Seventy six such sub arrays were attached to the upper surfaces of the wing and stabilizer. The entire solar array weighed 45 pounds and could deliver 2,500 watts, 45 amperes at 56 volts at sea level, air mass one, and sun overhead. In flight the available current increases with altitude as the atmospheric attenuation diminishes and more sunlight reaches the cells. The array voltage also increases as the cell temperature drops because of the colder atmosphere and the cooling effect of airflow over the cells. We calculated that maximum power would occur at about 30,000 feet altitude where the array should deliver 58 amps at 75 volts for a total power of 4,350 watts. In the early morning hours the low sun angle and the high atmospheric adsorption made take off difficult. Many time at 9AM in the morning we measured only 1400 to 1500 watts, just barely enough to maintain zero sink, never mind climb. The average efficiency of the solar array was 12.5 percent.

The Challenger Propulsion Subsystem

The propulsion subsystem used a high efficiency samarium cobalt permanent magnet DC motor driving a variable pitch 11 foot propeller through a 22 to 1 belt and chain speed reducer. The Astro Challenger 2500 Motor turned at 7,000 to 9,000 Rpm while the 11 foot prop turned at 320 to 350 Rpm. The Challenger motor used a 16 slot armature lamination and measured 2.062 inches in diameter by 3.92 inches long. The samarium cobalt magnets were about 1/8 inch thick and 4 inches long. Air gap flux density averaged 4,500 gauss while the flux density in the silicon steel Laminations was 17,000 gauss. At these high flux densities noticeable cogging occurred, enough so that the motor could not be turned over by hand. About 9 amps were required to start the motor turning but once turning the no load current dropped to a more reasonable 3 amps. Many time in the early morning with low sun, I would have to swing the prop by hand to get the motor running. The sight of me propping the Challenger after Ray in the cockpit yelled "Contact" never failed to amuse the onlookers. Special high altitude brushes were supplied by Kirkwood Carbon after we experienced some problems with earlier brushes. These new brushes worked perfectly and the brush wear after 25 hours of flying was not measurable. The 2 ½ Horse Power challenger motor measured 3 inches in diameter and was 5 inches long and weighed 6.1/2 pounds. Since we had anticipated crossing the Channel early in the spring, we had hoped to take the Challenger to the DuPont European Headquarters in Switzerland for a high altitude attempt. Our calculation indicated that the Challenger should have a service ceiling over 30,000 feet. And at this altitude we could expect the solar array to produce 4,300 watts. For this reason we installed a second Astro motor in tandem behind the original motor. All domestic flights were made with one motor; all foreign flights were made with two motors. The step down transmission used a 1/5 pitch timing belt one inch wide to transmit the motor power to a jack shaft. We mounted a 17 tooth timing pulley on the motor and a 72 tooth timing pulley on the jack shaft. The jack shaft in turn was fitted with a 12 tooth bicycle sprocket the drove the 62 tooth bicycle sprocket on the propeller through a standard 10 speed bicycle chain. As the airplane changed attitude and direction relative to the sun, the power from the solar array varies quite substantially. In order to maximize the power from the solar array a variable pitch propeller was used. The pilot had to change the pitch from time to time to keep the power maximized.

Early Flight Tests

The early flight tests of the Challenger were conducted at Shafter, California with a 45 pound battery consisting of 120 GE D size Nicads wired in two strings of 30 cell each. The weight and power of the Nicad battery simulated the expected weight and power of the solar arrays being fabricated at Astro Flight. We wanted to get some shake down flights on the Challenger before risking the solar array because we could not afford to break any cells in a possible mishap. Replacing the arrays would take six months and over one quarter million dollars. Steve Ptacek was the engineering test pilot for the first shake down flights. At that time Steve weighed 145 pounds at that weight challenger could only reach altitudes of a few hundred feet. Ninety five pound Janice Brown then tried her hand at flying the Challenger and made one battery powered flight that lasted 1 ½ hour and she reached altitudes of a few thousand feet. We felt that now we were ready to install the solar arrays. Two days before Thanksgiving Day, 1980 the Solar Challenger with pilot Janice Brown abroad made its first solar powered flight at El Mirage Glider port in the California desert. The results were sufficiently encouraging that DuPont asked us to take the Challenger to Marana Air Park new Tucson, Arizona. Our objective was to make the 100 mile from Marana to Phoenix. Janice made a number of attempts that winter but the farthest flight was only 30 miles. We returned to California and waited for spring weather. In late April and early May both Steve Ptacek who had slimmed down to 125 pounds and petite Janice Brown made a number of solar practice flights from Shafter Airport near Bakersfield, California. Steve had one flight of over six hours and covered 200 miles over a triangular course. Janice made a high altitude flight of over 16,000 feet. We figured that we were now ready for the English Channel, so in late May we packed up our gear and headed for Paris France. We made out base at Pointoise, a small airport about 20 miles north east of Paris. The flight plan was to fly from Pointoise to Manston RAF base in Kent, England. Manston was the home base for the Albatross in 1979 so many of the lads at the base remembered the MacCready crew. But we had forgotten just what kind of rotten weather there is on the English Channel or La Manche Diabolique as it is referred to in certain circles. The wind was constantly out of the north and we had overcast weather every morning. It was impossible to take off before noon and with a strong head wind and a 46 mph airplane we did not have enough daylight to make the 200 mile flight. There were a few days of strong winds and clear skies that probably would have made a flight to Bonn, West Germany possible, but our goal was England. In desperation we moved to Manston in the hope of making the reverse flight with the prevailing wind to our back. We stayed in Manston for 16 days. It was overcast and raining every day. Then Paul got word from the meteorologist that a high pressure area was building over the continent and that we might have favorable weather for a Pointoise to Manston attempt in two days. We packed up our gear and headed back to Pointoise. The next day was windy but we got the Challenger erected and ready to fly. The following morning July 7, 1981 the French weather was beautiful it was a prefect California Day. Steve Climbed aboard and we walked him out on the runway. Thousands of people were lined up on both sides of the runway waiting for the Challenger to do its thing. It was early in the morning and there was quite a bit of ground haze and the sun intensity was only 85 % or normal. Take of was a bit difficult. Steve made six or seven take off attempts before lifting off and heading for England. Paul and the DuPont team followed in a chase plane. Ray and I drove the Challenger Van in the vain attempt to keep up with Steve, but towing a trailer on the back roads of France made this impossible. Ray and I finally made it to Calais about 5 PM and were told that the Challenger had landed at Manston about one hour earlier. Steve made most of the flight at between 11,000 and 12,000 feet and averaged about 50 miles per hour. He circled Manston for about and hour before landing to let all the chase planes and reporters get through customs and lined up on the runway to photograph the landing. That night the RAF at Manston threw a big party for us all. We were treated like heroes. The Challenger sat silently and proudly in an RAF hangar. It had just made the world's first international solar flight.

The Solar Challenger Characteristics

Wing Span	46 feet 8 inches
Wing Area	235 square feet
Aspect Ratio	nine
Airfoil	Lissaman
Length	30 feet 4 inches
Empty Weight at channel crossing	220 pounds
Gross weight with 119 pound pilot	339 pounds
Solar Array	16, 128 cells
Cell Type	Spectrolab HS318
Cell Size	2 cm x 6 cm
Cell Short Circuit Current	500 ma
Cell Efficiency	12.5 percent
Array Power at sea level	2,500 watts
Array Power at 30,000 feet	4,300 watts
Motors	two Astro 2500
Motor rating	2.5 hp each
Motor Weight	6.5 pounds each
Motor best efficiency	82 percent
Speed Reducer	22 to 1 ratio
Variable Pitch Propeller	11 feet in diameter
Propeller Speed	350 Rpm
Aircraft Cruise Speed	46 miles per hour
Estimated service ceiling	30,000 feet

Summary

We have examined the progress made in the first decade in the age of solar flight. The logical questions now are: What would we like to do next? What kinds of improvements in technology can we expect? Are there any practical missions for solar powered air vehicles? What kinds of useful missions can a solar powered air vehicle perform better or at lower cost than other propulsion methods? What kind of things will advance the state of the art?

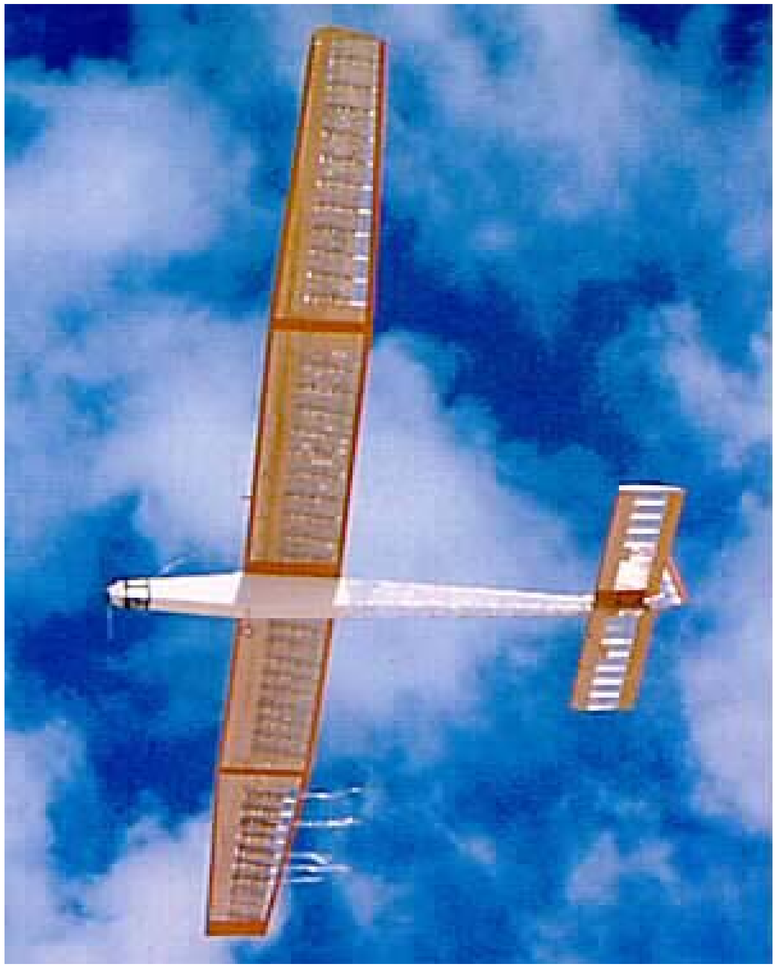
Let's look at the first question. We have demonstrated that the solar powered airplane can reach high altitudes and that is can carry man for hundreds of miles. Here is my priority for solar tasks yet undone. I am sure the reader can add a few of his own.

1. Sunrise demonstrated the feasibility of long duration flights at temperate latitudes. The next step would be to build a demonstration vehicle to do just that. A solar powered vehicle carrying a small communication relay could be built that could fly continuously. It could be used to provide direct communication between ground subscribers with low power radios over state wide areas. The investment cost might be low enough to attract risk capital. This might prove to be very useful in areas where direct communications are hindered by mountains.

2. A high altitude atmospheric probe for air sampling and assessment of winds and turbulence at altitudes of 100,000 feet or more could prove useful.
3. One might use a solar powered aircraft to observe the migration of birds over long distances. This sounds like a good project for the National Geographic or the Cousteau Society.
4. The Mega Buck Grand Prix. How about having a transcontinental solar air race in 1986 from Los Angeles to New York? Let's offer an attractive prize of say 1,000,000 dollars tax free. This race should receive good radio and TV coverage so that the investors could sell advertising time to more than make up for the prize money and logistics costs. The Mega Buck prize money should attract a lot of competitors and make for an exciting race.
5. A solar powered dirigible could carry a large load at low cost. Smaller vehicles could serve as observation platforms for sporting events and for traffic control.

What kind of improvements in technology can we expect and what effect will these improvements have on vehicle performance? First, Solar cell efficiency will improve. We saw cell efficiencies in 1975 on Sunrise II of 14 percent. We hear rumors of improved multi-junction solar cells with efficiencies of over 20 percent being worked on at IBM, Ford and Volvo. Improved efficiency means more power in less space and weight. Present cells have the equivalent of 600 watt hours per pound. At 20 percent efficiency the energy density would increase to 1000 watt hours per pound or about one half that of gasoline. Improved efficiency means a higher possible wing loading, higher speed, and a smaller structure that will be stronger and lighter and that will allow a higher payload fraction. At a solar cell efficiency of 40% the solar airplane will have performance approaching that of gasoline powered aircraft. Next improved battery technology will allow energy storage for night time operation. Since the present day solar cells have an energy density of 600 watt hours per pound we need a battery with at least this much energy density. Unfortunately today's Nicads have only 12 watt hours per pound, only one fiftieth that needed. We need a battery that can be charged in six hours and that can store 400 to 600 watt hours per pound.

Unmanned air vehicles usually carry complex electronic payloads. The revolution in micro electronics is making smaller and smaller payloads possible. This means that small solar powered drones with a small payload fraction can perform useful tasks. What other kinds of practical missions can the solar powered aircraft have? I am sure that there are many uses yet undreamed of for this clean, quiet and inexhaustible energy source,

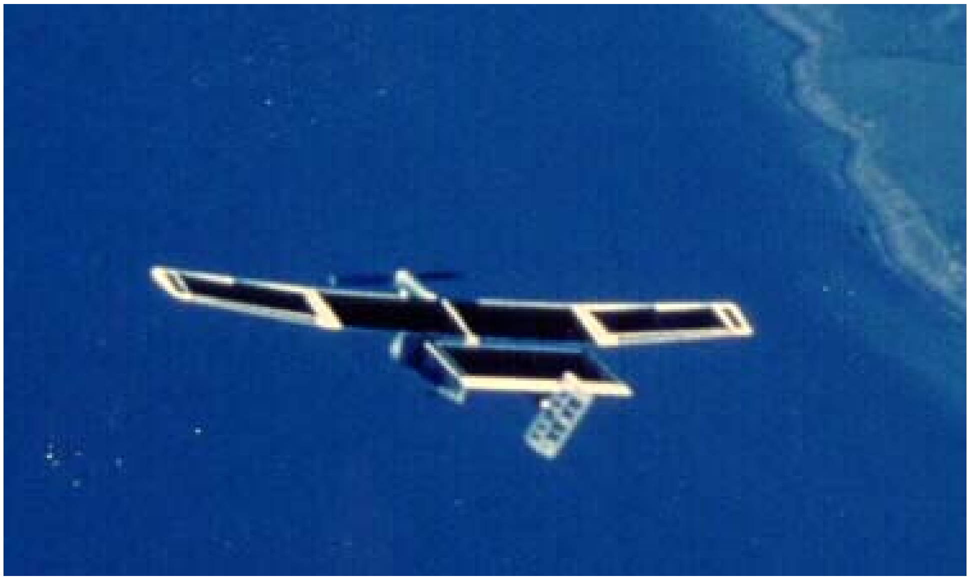


Sunrise I is made its historic worlds first solar powered flight on November 4, 1974 at Fort Irwin, California. Sunrise I is shown flying at 4,000 feet above the desert at Fort Irwin California.

Sunrise II ready for launch on Sept 12, 1975 at a dry lake near Mercury Nevada. The test site was part of Nellis Air Force Base. Shown in Photo are Stan Hall and Dan Lott on wing tips, Bob Imresek at the tail and the author running back to control station.

The Gossamer Penguin on its world first manned solar flight at Shafter, California on May 18, 1980. Young Marshall MacCready was the pilot, Ray Morgan up front, Blaine Rawdon under left wing and Author Bob Boucher taking up the rear. The Sunrise II solar panel was on loan from Astro Flight for the program.

Gunter Rochelt with his Solair I in Munich, Germany. We met Gunter with his Solair I at Biggen Hill while we were at Manston RAF base with our Solar Challenger waiting for clear skies.



The Dupont Solar Challenger at 12,000 feet crossing the English Channel on July 7, 1981. Steve Patcek Pilot.