SOLAR-POWERED AIRCRAFT DESIGN

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SUMMARY

Beginning with the present state of the art in cost-efficient solar technology, optimization of a solar-powered aircraft has shown possibilities of this new technique.

The following developments have improved solar-flight technology:

- high-precision aircraft construction of minimum weight;
- integration of the solar cells in the upper wing surface without aerodynamic or other losses;
- high-efficiency drive and propulsion system with variable pitch propeller, automatically controlled to attain maximum photovoltaic power output;
- a buffer battery of high power output for safe take-off and difficult flight incidents.

All these features have already been successfully tested on a model aircraft. A design proposal will be presented involving a high-efficiency solar powered aircraft with 25m wingspan capable of taking off and climbing up to an altitude of

450m equipped with a buffer battery.

Above this altitude, the aircraft is to fly and climb up further (up to 0.45m/sec.) by solar power alone.

1. INTRODUCTION

The photovoltaic or solar cell was invented in the USA in 1954. In the same year, Raspet discussed the possibility of solar-powered flight. People have dreamed of flying with the endless stream of energy from the sun long before the necessary technology even existed.

Twenty years later, in 1974 Astro Flight from Los Angeles successfully tested the 10m span solar model aircraft Sunrise (Ref. 1). The legendary flight of S. Ptacek from Paris to England with Paul MacCready's Solar Challenger on July 7, 1981 constituted a major breakthrough in solar powered flight (Ref. 2).

In 1980 the author began work on the propulsion system for the first German solar-powered aircraft Solair I, which made remarkable flights a year later (Ref. 5). After the Musculair 1 and 2 projects, the author continued developing advanced technology for solar powered flight with Franz Weibgerber.

2. DRIVE CONCEPTS

Because solar radiation possesses a very low energy density (about 1.0 kW/m^2 on the earth's surface) in comparison with the energy density of liquid fossil fusel (about 12 kWhr/kg), a solar aircraft must be extremely lightweight in design and draw its power from a highly efficient energy conversion process. However, no matter how light or energy efficient a solar-powered aircraft is, it will still be underpowered. On the other hand, solar energy is available as long as the sun shines with sufficient intensity.

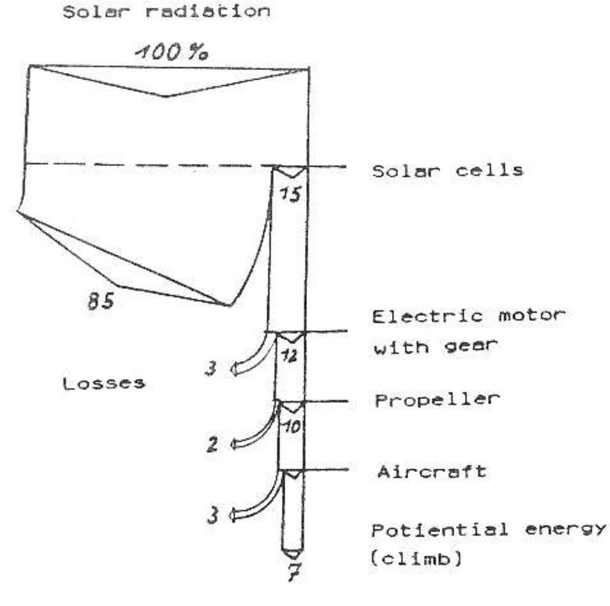


FIGURE 1. ENERGY BALANCE OF A SOLAR-POWERED AIRCRAFT.

Since very good solar flight weather is rather rare in Central Europe and many other areas, a solar aircraft's design should allow it to carry out a successful flight, even at 50 percent intensity (50 mW/cm^2).

Figure 1 shows the state of the art efficiencies of the different steps of converting solar radiation to climb of an aircraft.

In Figure 2, intensity measurements both vertical to the sun and horizontal to the earth's surface are given for a typical good sunny day.

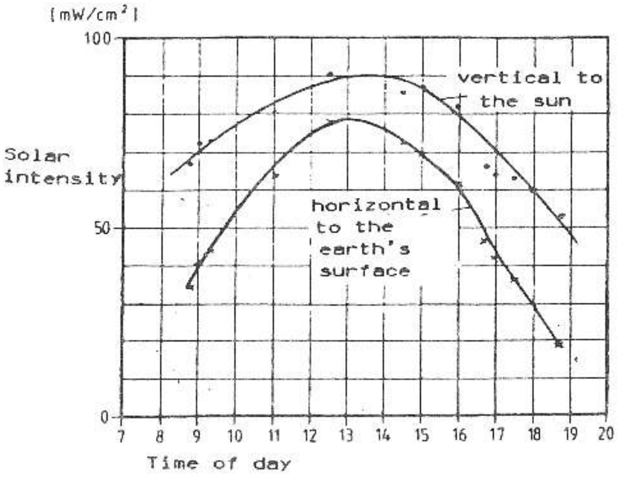


FIGURE 2. SOLAR RADIATION AT NURNBERG ON MAY 9, 1987.

The main influences on the energy balance shown in Figure 1 are expressed as an analytical function of the aircraft's climbing velocity:

$$V_s \approx (E.A_s.N_s.N_m.N_p/W) - (2.W/S.\pi.e.b^2.V_c) - (s.V_c^3\Sigma(A_i.C_{di})/2.W);$$

V_s = climbing velocity
E = intensity of solar radiation
A_s = solar cell surface
N_s = solar cell efficiency
N_m = motor ang gear efficiency
N_p = propeller efficiency
W = total flying mass
S = air density
e = correction factor for non elliptical lift distribution
b = wing span
V_c = flying velocity
C_{di} = drag coefficient of a plane component
A_i = exposed area of a plane component

All these influences and their different interactions cannot be discussed here, but they must be considered in calculations.

What is important for solar aircraft design:

- high solar cell efficiency; a good compromise is obtained with thin monocrystalline cells with about 15 percent effi-

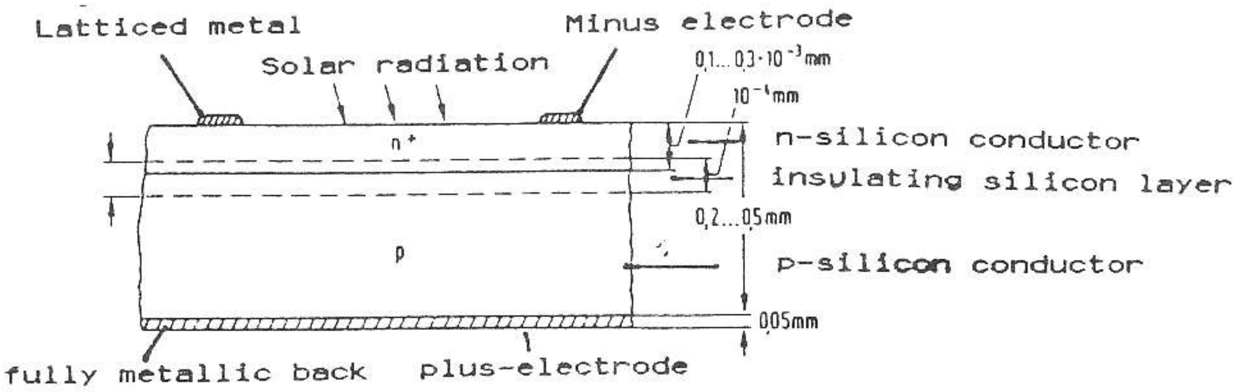


FIGURE 3. STRUCTURE OF A PHOTOVOLTAIC SILICON CELL.

ciency which cost about $10 per watt installed;
- minimum weight of all components (pilot included);
- high aerodynamic quality which means high profile accuracy and surface finish to attain as much laminar flow as possible;
- good stability and controllability;
- highly efficient motor, gearbox and propeller;
- optimum adaption of all individual components to each other over a wide operating range;
- safety, reliability of all components mechanical, electrical, electronic, aerodynamic and flight mechanical;
- ease in handling and operation.

2.1 Solar Cell

The structure of a monocrystalline silicone cell is shown in the section drawing Figure 3 (Ref. 3).

The operating characteristics (Figure 4) show that voltage under no load operation U first rapidly rises with solar intensity and then slowly rises to the saturation point of about 0.6 volt. The short circuit current I_k is proportional to radiation intensity.

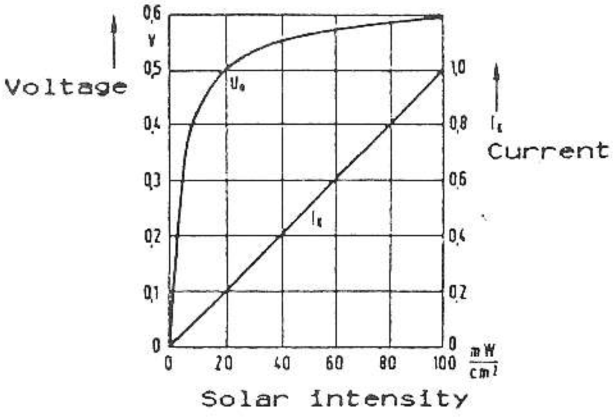


FIGURE 4. NO LOAD VOLTAGE AND SCORT CIRCUIT CURRENT DEPENDENT ON SOLAR INTENSITY.

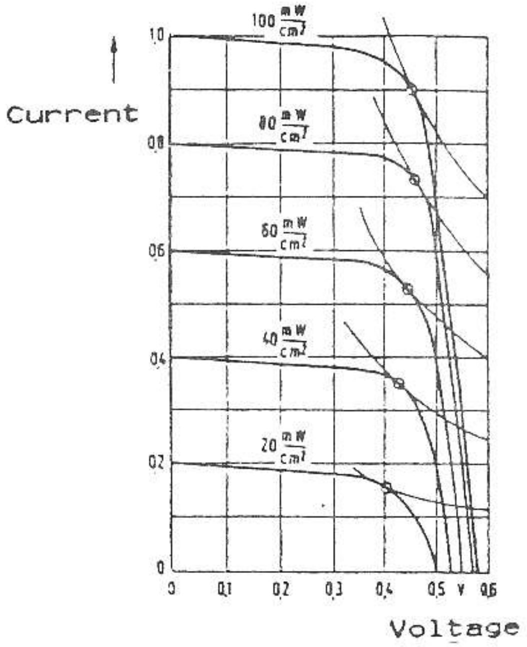


FIGURE 5. VOLTAGE-CURRENT-CHARACTERISTIC FOR DIFFERENT SOLAR INTENSITIES.

Figure 5 gives the voltage — current characteristics for different solar intensities with the point of maximum power output. The power — voltage characteristics (Figure 6) with the power peak in a small range emphasizes the importance of a good power adaption. Misadaption at one element in the energy conversion chair drastically reduces power output of the whole system. Therefore, a control system with minimum losses is necessary to keep the system working efficiently under changing flight and solar radiation conditions.

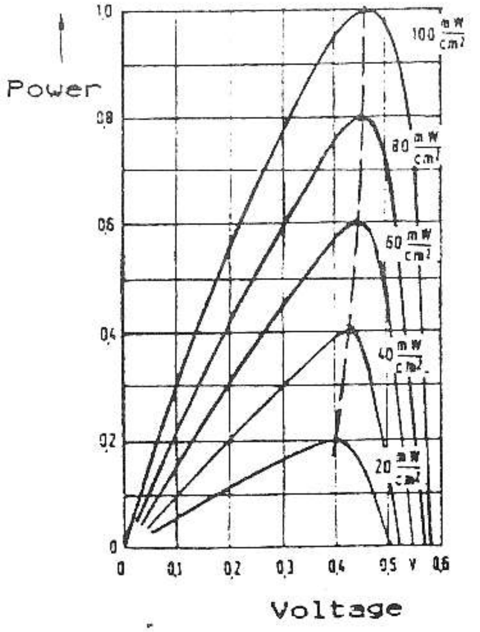


FIGURE 6. POWER- VOLTAGE-CHARACTERISTIC FOR DIFFERENT SOLAR INTENSITIES.

Temperature has a great influence on the operating characteristics of solar cells (Figure 7). Current slightly rises whereas voltage and power output significantly drop by about 1/2 percent per deg. C increase. Intensive cell cooling therefore, serves not only to prevent buckling, but also to maintain voltage and power output at acceptable levels.

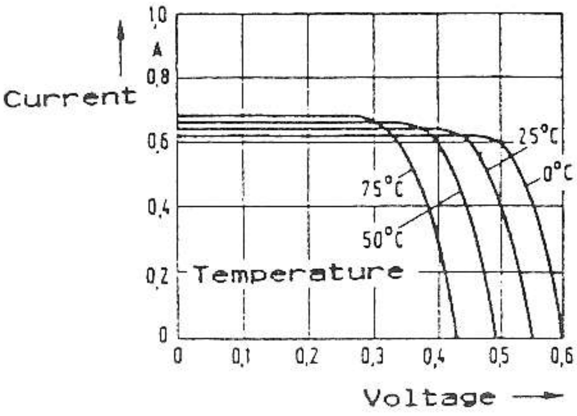


FIGURE 7. INFLUENCE OF TEMPERATURE ON THE VOLTAGE-CURRENT-CHARACTERISTIC.

2.2 Electric Motor

Brushless direct-current motors with high-flux permanent magnets (samarium - cobalt or better neodym) should be used to get light weight and high efficiency. Whereas, bell shaped rotor motors are advantageous for low-power (model) aircraft, iron rotor motors are necessary for higher power aircraft, because of their much better power to weight ratio.

The operating characteristics of a small bell shaped rotor motor (Figue 8) show that high efficiency can be reached over a small operating range with comparatively low power only. That is typical for all electric motors. To operate the motor efficiently at the power required for fast climb much high voltage than normal is necessary. The rotor must, therefore, be carefully dynamically balanced.

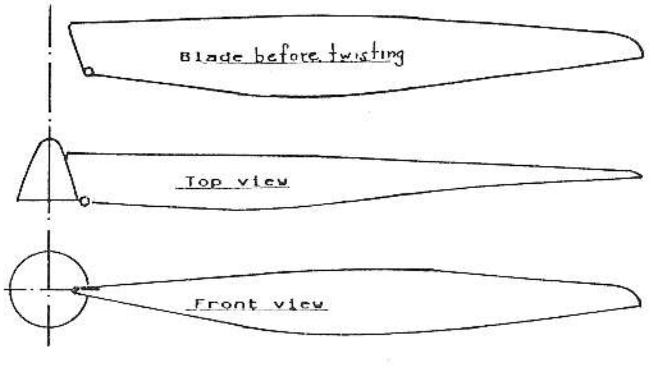
As highly efficient propellers run at a low speed, gears must be interconnected. Small, lightweight and efficient planetary gears must be provided.

2.3 Propeller

High efficient propellers are low loaded, large in diameter have a high pitch (about diameter) and run slowly (Ref. 4). The minimum induced loss technique is necessary to achieve high efficiency over a wide range of flying velocities. The propeller on the world record man — powered aircraft Musculair 1 and 2 was originally optimized for the solar powered aircraft Solair I in 1980 (Ref. 6).

The most efficient means of getting maximum photovoltaic power to the aircraft is with an electronically controlled variable pitch propeller. Although designed in 1980, this type of propeller could be installed and tested in solar test model Solariane in 1988.

The blade of the model propeller is typical for minimum induced loss design. The thrust (Figure 9) and efficiency graphs (Figures 10 and 11) demonstrate the wide operating range of a variable pitch propeller.



Desigh data		
	Thrust	2.0 N
	Flying velocity	8.0 m/sec.
	Speed	920 rpm
	Power absorbed	19 Watts
	Efficiency	84 %
	Blade angle adjustment	±10 deg
	Diameter/pitch	600/650 mm

FIGURE 9. VARIABLE PITCH PROPELLER OF SOLAR MODEL AIRCRAFT.

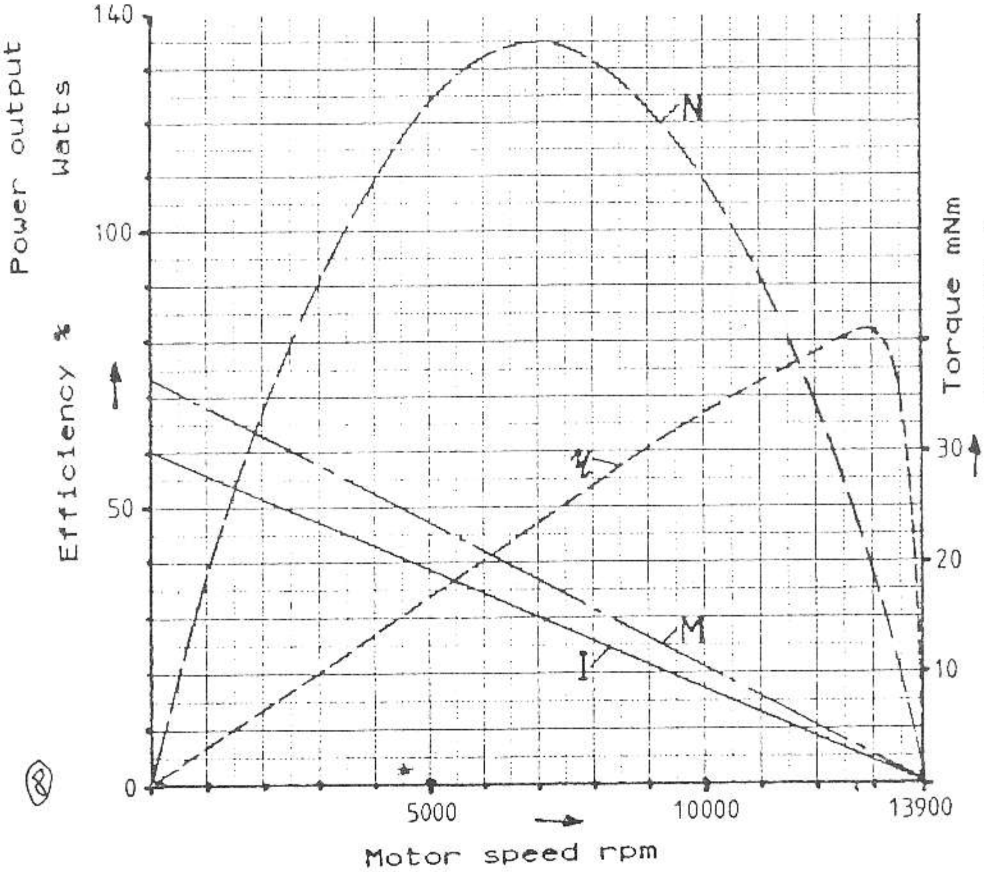


FIGURE 8. MOTOR-CHARACTERISTIC CURVES, FAULHABER BELL-SHAPED ROTOR MOTOR 3557 KR006C AT 18 VOLTS.

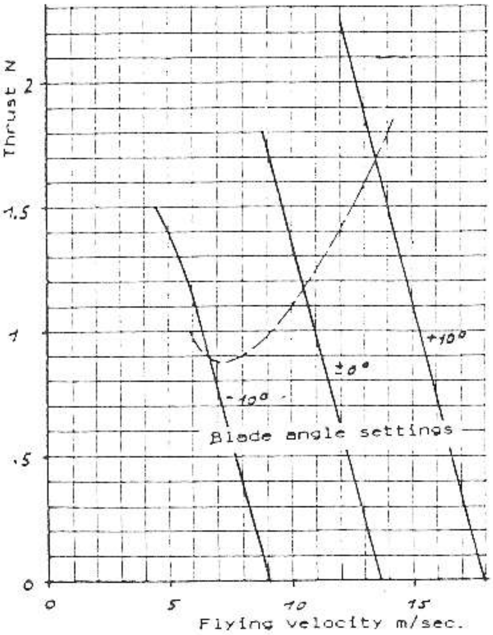


FIGURE 10. PROPELLER THRUST WITH THREE DIFFERENT BLADE ANGLE SETTINGS AND WITH MODEL AIRCRAFT DRAG.

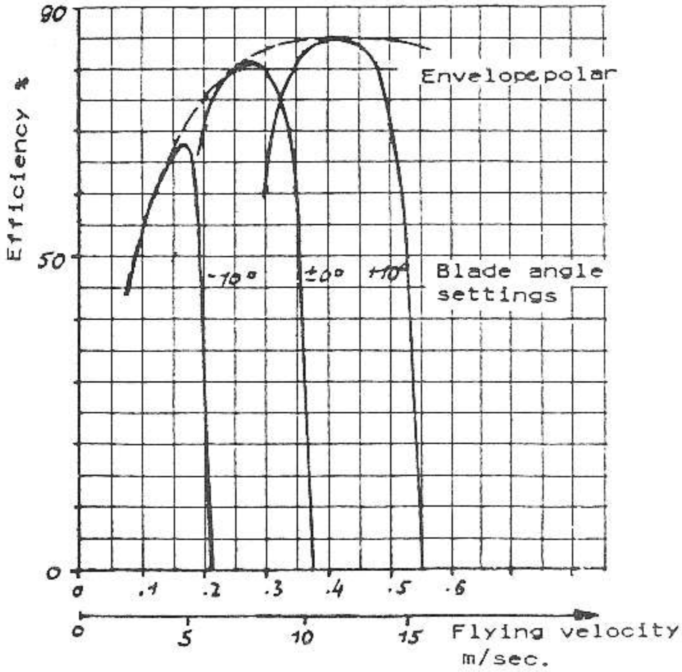


FIGURE 11. PROPELLER EFFICIENCY.

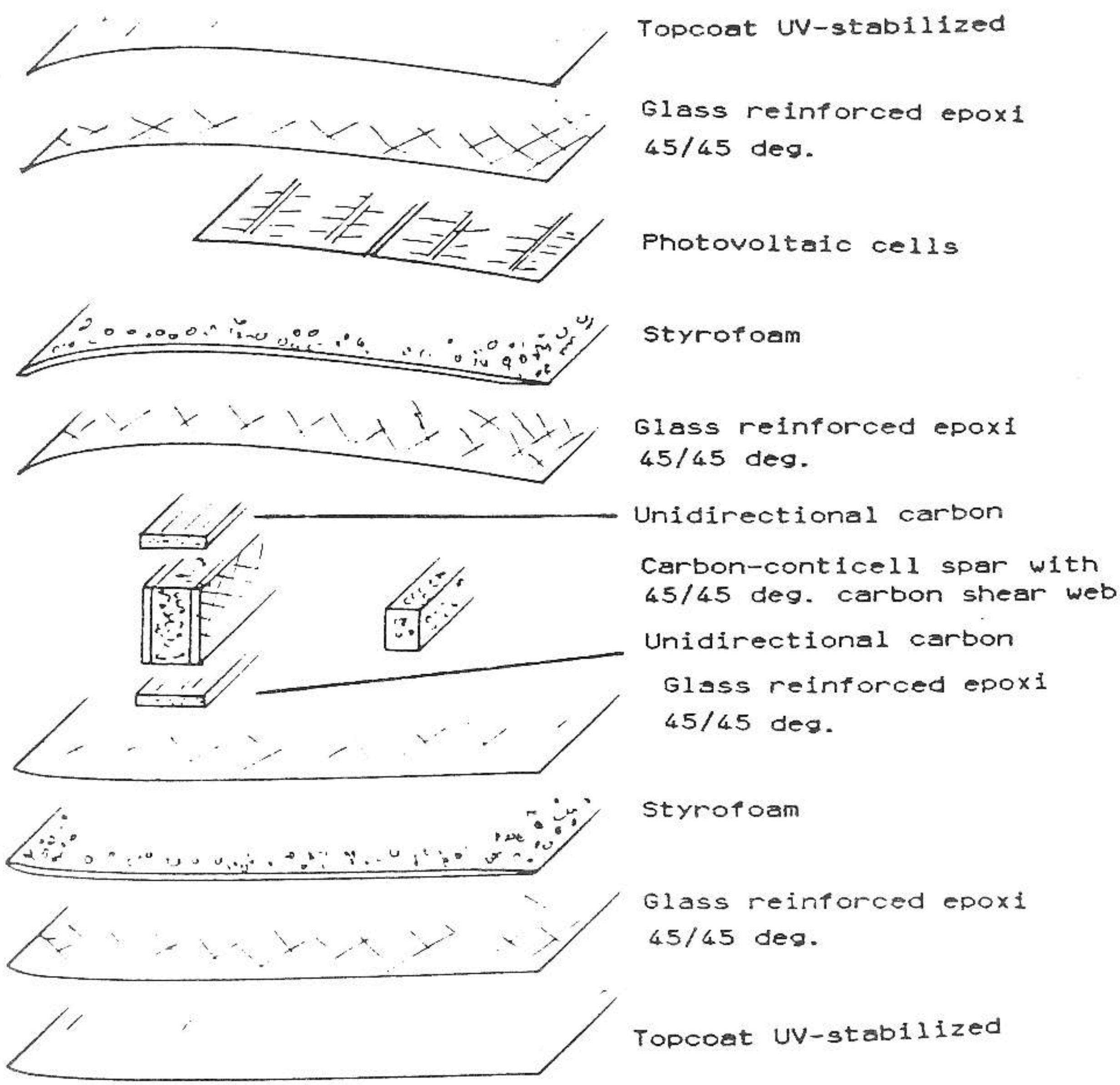


FIGURE 12. WING STRUCTURE IN FIBRE REINFORCED EPOXI-PLASTICFOAM SANDWICH CONSTRUCTION WITH INTEGRATED SOLAR CELLS.

2.4 Solar Cell Circuits

Optimum voltage lies between 60 and 90 volts. So the photovoltaic cells have to be soldered to strings of 120 to 180 cells in series, parallel to which run a number of strings connected to a panel. Forming subpanels or cross-connections in between parallel strings permits the current to bypass broken cells without overloading adjacent cells.

The solar cells should be so arranged at the wing surface that at least 4 or more panels are formed, which are connected through a shottky diode and a switch to the panel bus. Normally, all panels are used and power is regulated by the elctronic propeller pitch control.

3. WING STRUCTURE

Extreme light weight, high strength with high accuracy and surface finish can be realized with integrated plastic foam — fiber reinforced plastic sandwich construction in precise female molds similar to those of gliders.

Frenz Weibgerber and the author carried out many tests to integrate as much as possible of the breakable solar cells in the upper rear region of the wing.

This integration should lead neither to aerodynamical, optical or electrical losses, nor cause strength, expansion, buckling or heat dissapation problems. We successfully applied our development on our test model Solariane and, surpris-

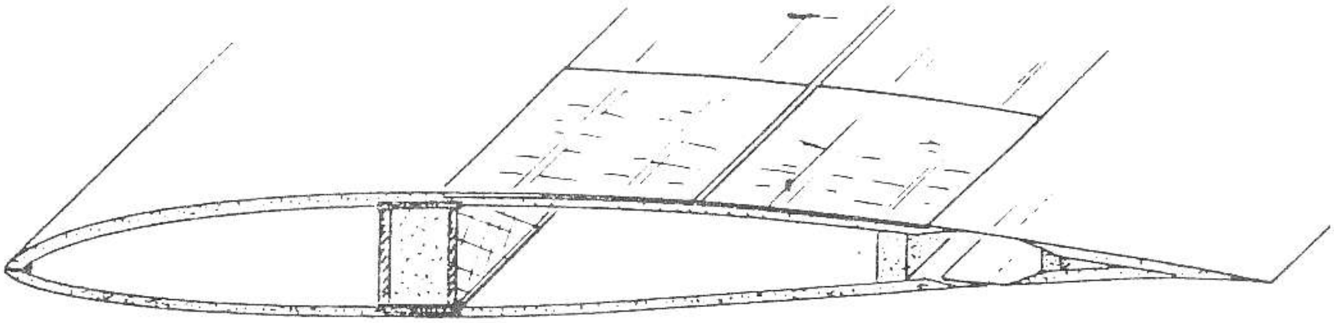


FIGURE 13. WING STRUCTURE WITH INTEGRATED SOLAR CELLS AND FLEXIBLE JOINT FLAPS.

ingly, could not find power losses due to the thin glassfiber -epoxy layer over the cells which seems to be optically active.

Although total wing weights as low as to 1.2 kg/m ^{2} (with 55 percent solar cell covering) could be achieved, minimum weight for an aircraft should be over 3 kg/m ^{2} for stability reasons.

Figures 12 and 13 show how to install solar cells airfoil-true in the upper shell of the sandwich wing. Protected from moisture and other environmental influences, optically clean and air cooled photovoltaic cells do not disturb laminar flow.

4. TEST MODEL SOLARIANE

The aforementioned technology was tested on a radio controlled model plane with 3.08m span, total mass 1.83 kg, 0.85m ^{2} wing area and 44 polycrystalline cells each 0.010 m ^{2} in size (Ref. 7). Everything worked well from the very beginning.

It is possible to take off safely at 50 mW/cm ^{2} radiation intensity and to maintain altitude in calm air even at 30 mW/cm ^{2}. Control of the variable-pitch propeller proved not to be very critical. A wide speed range can be flown because of the low drag resulting from advanced design and fiber reinforced composite sandwich construction.

On the day of the first flight, Franz Weibgerber was able to attain an official world speed record with 66.22 km/hr at Bremen/North Germany on July 5, 1987.

We are presently testing a wing with thin monocrystalline cells and higher efficiency (15 instead 10 percent). Safe take offs are, therefore, possible even at 30 mW/cm ^{2} solar intensity.

5. OPTIMIZATION OF THE SOLAR POWERED AIRCRAFT SOLARISE

Little research was required to achieve the usual conventional concept. The author's experience with the canard Solair I was similar to that reported by A. W. Blackburn at the XX OSTIV Congress at Benalla (Ref. 8).

Tailless configurations seem to be advantageous as no separate stabilizer is required. This allows for a small fuselage and reduces weight, but much research remains to be done. It will be interesting to see what results the SB 13 project will bring (Ref. 8).

Optimization of conventional aircraft with wing spans between 15 and 25 m and chords between 0.8 and 1.5 m show best glide results (Figure 14) at 25 m span and 0.8 m chord with the best glide ratio of 37 at 13 to 14 m/s velocity and 0.31 m/s minimum sinking velocity close to stall speed.

A slight reduction in sinking velocity is certainly attainable but leads to a huge aircraft similar to the man powered aircraft Daedalus.

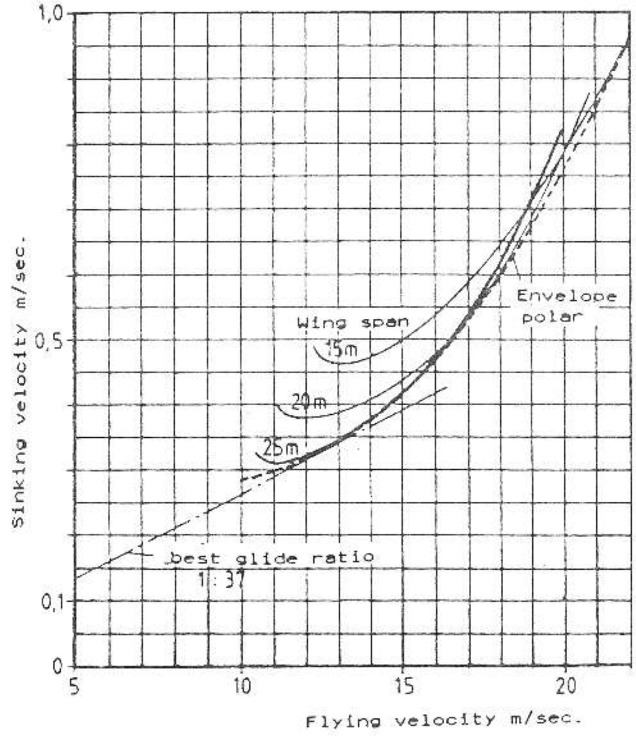


FIGURE 14. SINKING VELOCITY POLARS OF SOLAR POWERED AIRCRAFT WITH VARYING WING SPANS.

AIRCRAFT OR MODEL	DESIGNERS	PHOTO-VOLTAIC POWER AT 100 mW/CMWATTS	TOTAL FLYING MASS KG	WING SPAN M	SPECIFIC SOLAR POWER WATTS/KG	MAX CLIMB-M/S	FLYING VELOCITY SOL. POWER M/SEC.	REMARKS
SUNRISE	R.J. BOUCHER	570	10.34	9.75	55.1	2	6.1-9.2	UNMANNED HIGH FLYING MODEL AIRCRAFT
SOLAR CHALLENGER	P.MacREADY	2500	145	14.3	14.3	0.75	8.5-16.1	KREMER-PRIZE FOR PARIS TO ENGLAND FLIGHT IN JULY '81.
SOLAIR I	G. ROCHELT	2200	180	16.0	12.2	0.2	8-13	6 HOUR FLIGHT IN '83 WITH STORED ENERGY FROM NI-CAD CELLS. CLIMB 1/M/SEC WITH BATTERIES.
SOLUS SOLAR	H. BRUB	69	2.22	3.2	31.1	0.75	5.5-9	DURATION FLIGHT WORLD RECORD:3HR,4MIN,54SEC IN '84.
POLY	H. BRUB	70	2.48	3.42	28.3	0.65	5.5-9	DISTANCE WORLD RECORD 43.5 KM IN '86.
SOLARIANE	F.WEIBGERBER E.SCHOBERL	44	1.83	3.08	24.4	0.8	6-17	SPEED WORLD RECORD 62.22 KM/HR IN '87.
SOLARISE	F. WEIBGERBER E.SCHOBERL	2200	195	25	11.3	0.45	11.5-18	WITH BUFFERED ENERGY 2.5 M/SEC CLIMB FOR 3 MIN. OR 35M/SEC. SPEEDFLIGHT.

TAB LE 1: MAIN TECHNICAL DATA OF SOLAR-POWERED MODEL AND AIRCRAFT PROJECTS

	OPEN CLASS GLIDER	SOLAR POWERED AIRCRAFT	MAN POWEREDAIRCRAFT
TYPE	ASW22b	SOLARISE	CYCLAIR
WING SPAN	25 M	25M	25 M
WING AREA	16,31M	20,70M	18,20M
ASPECT RATIO	38,32	30,2	34,3
AIRFOIL ROOT MIDDLE TIP	HQ 17 HQ17 DDU 84-132V3	FX60-126 FX60-126 FX60-126	FX76-160/MP FX76-140/MP
TOTAL FLYING MASS AT PAYLOAD	665-750 KG	195 KG 60 KG	86 KG 55 KG
WING LOADING	32-46 KG/M^2	9,42	4,67
MINIMUM VELOCITY	18,05-21,1 M/S	11,5	7,8
MAXIMUM VELOCITY	69,45 M/S	35	12,5
MINIMUM SINKING VELOCITY AT WING LOADING	0,41 M/S 32 KG/M^2	0,31	0,20
BEST GLIDE RATIO AT WING LOADING	<60 46 KG/M^2	37	44*)
MINIMUM SOARING REQUIREMENT	2715 WATTS	593	165*)

*)WITH GROUND EFFECT AT APPROXIMATELY 5 M ALTITUDE

TABLE 2: COMPARISON OF OPEN CLASS GLIDER WITH MAN POWERED AIRCRAFT AND SOLAR POWERED AIRCRAFT. DESIGN FOR STATE OF THE ART CONDITIONS, INCLUDING: GOOD LAMINAR FLOW AIRFOILS WITH SAFE STALL CHARACTERISTICS, OPTOMIZATION FOR BEST GLIDE RATIO, AND CARBON FIBRE COMPOSITE STRUCTURE WITH FIBRE COMPOSITE PLASTIC FOAM SANDWICH COVERING.

TYPE CONSTRUCTION	SOLAR-POWERED AIRCRAFT CFRP-GFRP PLASTIC FOAM SANDWICH CONSTRUCTION WITH INTEGRATED SOLAR CELLS
WING SPAN	25 M
WING AREA	20,7 M^2
ASPECT RATIO	30,2
WING AIRFOIL	FX 60-126
CHORD: ROOT/MIDDLE/TIP	1,00/0,85/0,65 M
ELEVATOR AREA	1,95 M^2
AIRFOIL (ELEVATOR & RUDDER)	NACA 0009
EMPTY MASS	135 KG
PAYLOAD	60 KG (50-90 KG)
DESIGN LOAD	+6/-3 G
WING LOADING	9,42 KG/M^2 (8,94-10,87 KG/M^2)
MINIMUM VELOCITY	11,5 M/S
MAXIMUM DESIGN VELOCITY	35 M/S
MINIMUM SINKING VELOCITY	0,31 M/S AT 11,5 M/S
BEST GLIDE RATIO	37 AT 13,5 M/S
MAXIMUM CLIMB WITH SOLAR ENERGY	0,45 M/S
CLIMB WITH BATTERY POWER	2,5 M/S
SOLAR CELLS FOR PROPULSION	14,5 M^2 MONOCRYSTALLINE SILICON CELLS WITH 15% EFFICIENCY
POWER OUTPUT	220 WATTS AT 100 mW/CM^2 RADIATION
SOLAR CELLS FOR INSTRUMENTS,ELECTRONICS AND RADIO	0.7 M^2 MONOCRYSTALLINE CELLS IN ELEVATOR
BUFFER BATTERIES	14 KG NI-CAD HIGH CAP. BATTERIES WITH 0.5 KW/HR NET CAPACITY
MAXIMUM POWER OUTPUT	10 KW FOR 3 MINUTES
ELECTRIC MOTORS	2 BRUSHLESS DC MOTORS WITH SmCo-MAGNETS
VOLTAGE	70/115 V
MAXIMUM POWER OUTPUT	5,0 KW
EFFICIENCY	>89% AT 70 V AND 1 KW
GEAR	ONE-STEP CYCLO-GEAR
EFFICIENCY	>97%
PROPELLER	2 VARIABLE PITCH FOLDING PROPELLER
DIAMETER	2.0 M
SPEED	480 RPM
EFFICIENCY	>86% AT 70 N THRUST AND 13 M/S
SOLAR POWER CONTROLLER	ELECTRONIC CONTROLLER SETS PROPELLER PITCH TO MAXIMUM PHOTOVOLTAIC POWER OUTPUT

TABLE 3: TECHNICAL DATA OF SOLAR-POWERED AIRCRAFT-SOLARISE.

When comparing this optimization with man powered aircraft and open class gliders under the same state-of-the-art conditions, including:

- optimization for the best glide ratio,
- good laminar-flow airfoils with safe stall characteristics,
- carbon fiber composite structure with fiber composite sandwich,

nearly the same configuration is the result (Table 2).

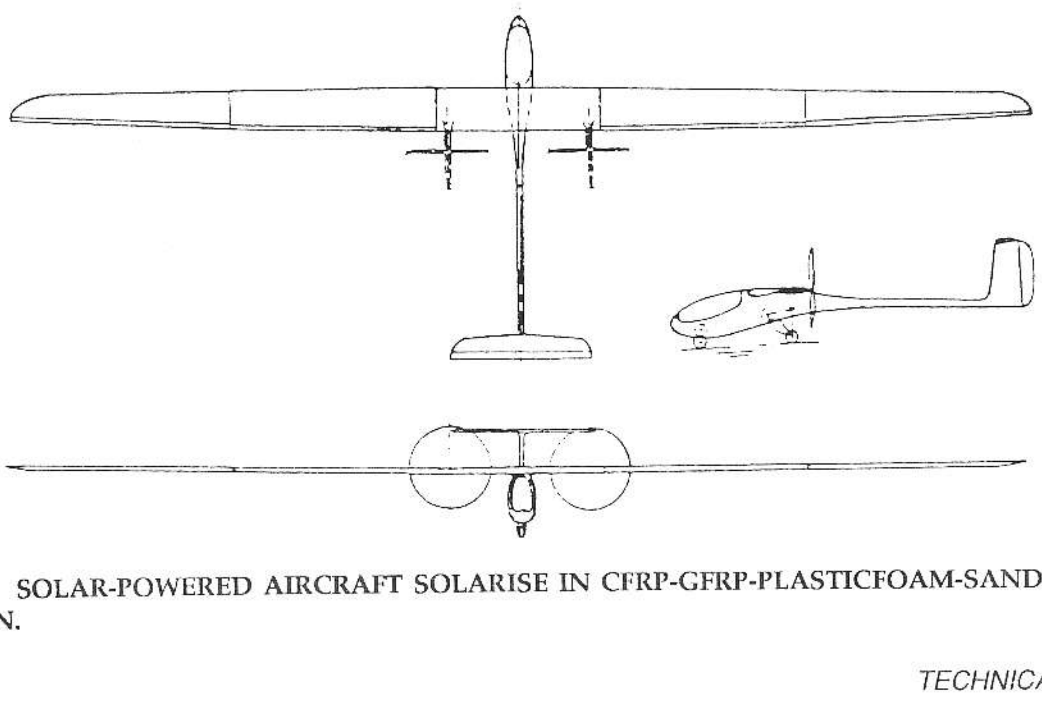


FIGURE 15. SOLAR-POWERED AIRCRAFT SOLARISE IN CFRP-GFRP-PLASTICFOAM-SANDWICH CONSTRUCTION.

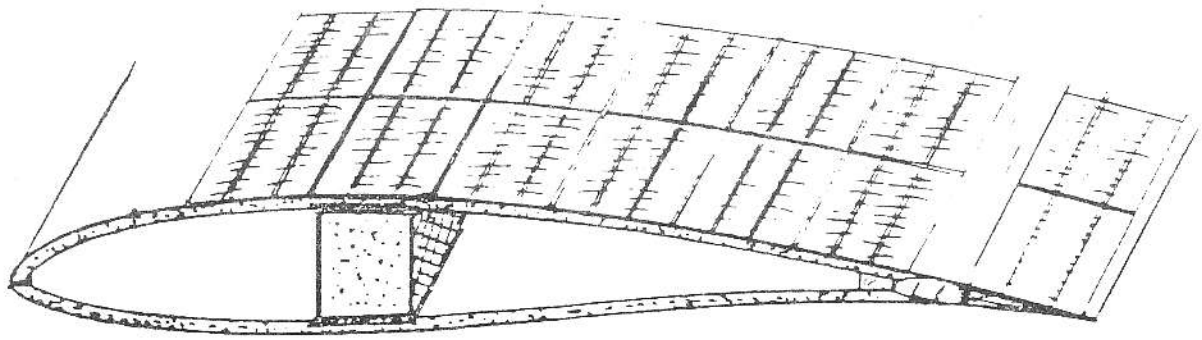


FIGURE 16. STRUCTURE OF THE WING WITH INTEGRATED SOLAR CELLS AIRFOIL FX60-126-.

Despite the rather different weights and flying velocities of man powered aircraft, solar powered aircraft and open class gliders have the same optimum span and nearly the same wing area (and aspect ratio).

The Solarise concept (Figure 16) indicates how a solar powered aircraft can be realized with lightweight, high precision construction, integrated solar cell panels and an advanced propulsion system.

For a safe take off and 3 minute climb at 2.5 m/sec. to an altitude of about 450 m, 10 kW of electric power is required for which approximately 15 kg nickel-cadmium batteries must be installed. They can be recharged under intensive solar radiation within half an hour when thermaling is employed (thermal is a powerful kind of solar energy). 2.2 kW of photovoltaic power (at 100 mW/cm ^{2} is sufficient to produce a slight but steady climb of about 0.45 m/s.

The Wortmann airfoil FX 60-126, recommended by L. M. M. Boermans Delft University, offers not only good performance at low Reynolds numbers (0.5 to 1.0 x 10 ^{6}) but has a small curvature at the upper side for easy installation of (a maximum number of solar cells) about 70 percent of the wing surface.

The solar cells are divided into at least 8 panels in the wings, whereas the 0.7 m^2 panel in the stabilizer supplies the instruments, controls, radio and batteries for this equipment. The power batteries consisting of 6 groups can be electronically switched over from charging and cross country flight with normal voltage (about 15 minutes power capacity from batteries only) to take off or fast climb with higher voltage and power (about 3 minutes capacity). Charging is also electronically controlled to avoid overloading.

Two drive units, each consisting of a fast running brushless DC motor, a planetary gear and a variable-pitch propeller, arranged behind the wings, convert nearly 75 percent of the photovoltaic power to useful thrust energy.

The Solarise study represents what can be presently achieved utilizing available economical technology and the construction methods developed.

After testing our new solar cell wing in our model aircraft, we will build a full scale wing section for Solarise.

6. APPLICATION OF SOLAR POWERED AIRCRAFT

With the technology available, an unmanned aircraft could be built capable of climbing up to the stratosphere during daylight hours, storing solar energy in the form of altitude gain and in chemical form in charging buffer batteries. This energy could be sufficient to keep the aircraft aloft at night so that the cycle could be repeated each day (Ref. 2).

Although such an aircraft would have a limited payload and flying velocity, it could serve as a useful meteorological, survey or relay platform.

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