DEVELOPMENT OF A SELF-LAUNCHING SOLAR POWERED SAILPLANE

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1. INTRODUCTION

The idea of launching a plane by solar energy is not a novelty. ((1), (2).) Table 1 gives a survey of the man-carrying solar-powered planes which have so far been realized.

We have new materials today, and there are a lot of new developments in the area of solar cells, electronic controls and electrical engines. One of the biggest technical challenges is the realization of a high efficient, lightweight propulsion system with a flexible photovoltaic generator an the construction of an aircraft according to the following requirements:

- self-launchable with battery power
- climb with 2m/s to an altitude of min. 500m
- horizontal flight only with solarpower
- payload 60 to 90kg
- structural strenght min. +4 / -2.69

2. SOLAR IRRADIANCE

The available solar irradiance depends on the location, season, time of the day and altitude. Figure 1 illustrates the seasonal dependency with the ten year means of monthly means of daily sums on a horizontal plane in Stuttgart.

This typical energy distribution for European moderate climates should be taken into account during the design process of solar powered systems. For systems with a very small or even without additional storage elements the maximal available irradiance is additionally very important. It makes no sense to develop a solar powered system which requires an irradiance of much more than 500 W/m². This value can be reached from April to September for at least 5 hours a day.

Name	Gossamer Penguin	Solar Challenger	Solair I
Builder	Paul Mac Cready	Paul Mac Cready	Günter Rochelt
first flight	1978	1980	1980
Wing span	21.9m	14.3	16.00m
Wing area			15.04m²
HLW-area			3.66m²
empty weight	31kg	92kg	120kg
maximum load	44kg	48kg	60kg
loading factor	very low	+4 / -2.6 g	+2.5 / -1.4 g

TABLE 1. Existing solar powered planes

3. SOLAR CELLS AND MODULES

The technical requirements for the photovoltaic modules can be summarized as follows:

1) high area related power [Watt/m²]
2) high mass related power [Watt/kg]
3) mechanical flexibility and
4) weather proof.

The investigation has to lead to a solar generator with maximum power output per weight, because in general the main restriction is the weight. Conventional PV modules in glass/ glass or glass/ plastic technology with crystalline solar cells achieve values either up to 150 Watt/m² or up to 12 Watt/kg (see Table 2). Recently announced developments for amorphous silicon solar cell films (Sanyo) promise an adequate solution for two of the require-

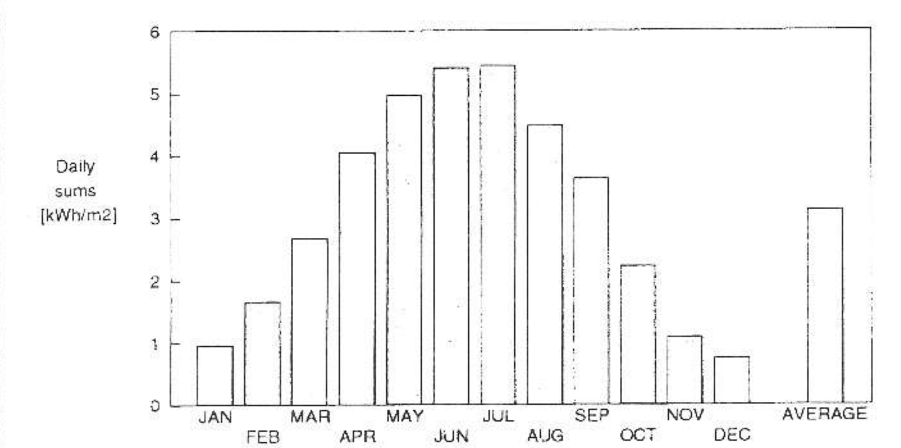

FIGURE 1. Ten years means of monthly means of daily radiation sum on a horizontal plane in Stuttgart.

ments [2), 3)], but need too much area for an application on an aircraft wing.

There are two possible approaches in order to meet all requirements. One is the realization of ultra lightweight crystalline silicon foil modules. Figure 2 illustrates the schematic construction of the developed foil module and Table 2 lists the achieved values. The second is the very similar but uses thin glassfiber layers instead of the Esther-Venyl-Acetat (EVA) to cover the cells. The mechanical and electrical properties are almost the same.

4.1 Structural Tests with Lightweight Solar Modules

In order to determine the mechanical flexibility properties several static and dynamic load tests have been carried out with samples of embedded solar cells.

At the static load test a line load was applied to module samples (Figure 2). Deflection was adjusted with a micrometer gauge and the resulting force to the foil module was measured with a load cell. This experiment was carried out at samples with different thickness of the embedding material until failure of the solar cells. The minimal bend radius for a construction according to Figure 2 is approx. 250 mm.

Modules can be exposed to rapid changing load conditions during flight operation, therefore further dynamic load tests have been carried out. Embedded solar cells are deflected with a frequency of 20 and 30 Hz within 20% and 100% of maximal deflection for several millions of cycles. The experimental setup is shown in Figure 4.

All dynamic load tests started with an initial stress due to deflection of the solar cells of 1 mm (solar cell width: 100mm, see Figure 2. Then maximum deflection was increased in 0.5mm steps after millions of load cycles each time. Frequency was varied between 20Hz and 30Hz. After twelve million load cycles without any negative effect maximum deflection was adjusted in the critical break range of 6mm. After fifteen thousand load cycles a power reduction of 50% could be observed.

Following analysis of electrical behavior of foil modules with broken solar cells showed significant decrease of the fill factor, but there was no total electrical failure.

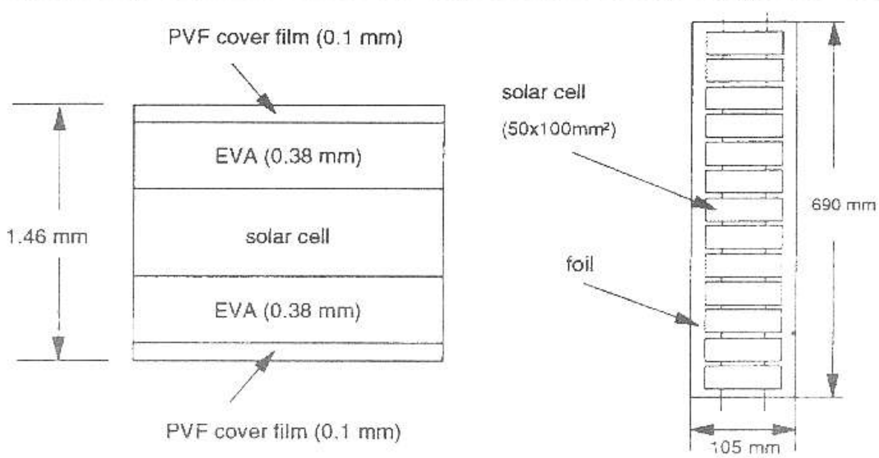

FIGURE 2. Schematic construction of a EVA-foil module (cross section and top view).

Module Type	Area per power [m²/kW]	Total mass per power [g/W]	Mechanical flexibility	Commercial available
BP Solar "BP 495" mono-c-Si, glass/PVF, with frame, η=15.1%	6.67	83.5	no	yes
Sovonics "RL 102" a-Si, polymer encapsul., without frame, η=6.4%	15.6	62.5	yes	yes
Sanyo (amorphous-Si)	> 25 (?)	5	yes	??
Foil Module (Fig. A)	*6.75*	*12.2*	*yes*	*yes*

TABLE 2. Characteristic numbers for selected PV Modules.

4. BATTERIES

Lead acid batteries are widelyspread and relatively cheap but with a poor energy density. Ni/Cd-accumulators have a higher capacily per mass and are quickly chargeable and dischargeable owing to their small internal resistance. A new development is the nickel/hydrid-cell with a 50 to 100% higher energy density compared to Ni/

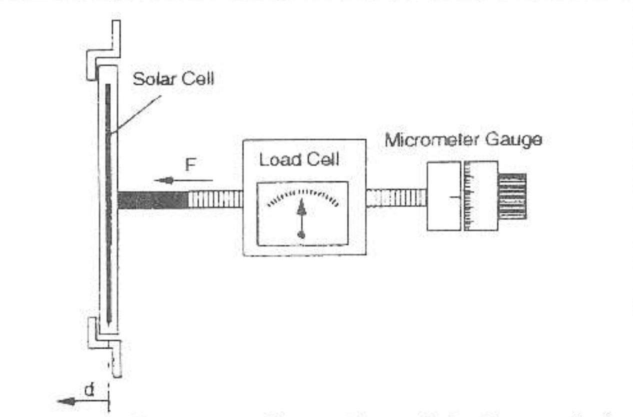

FIGURE 3. Experimental setup for static load tests of solar cells.

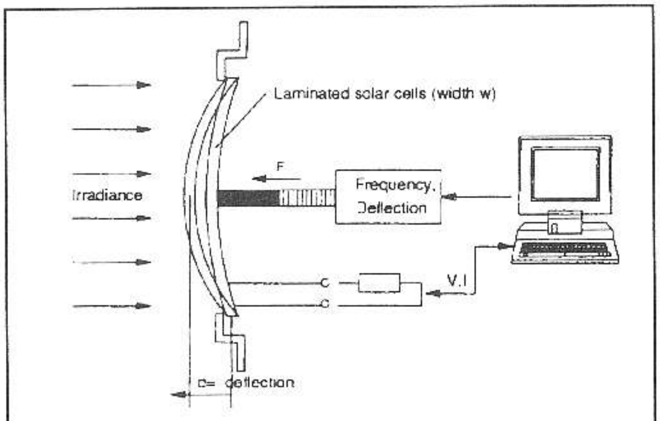

FIGURE 4. Experimental setup for dynamic load tests of solar cells.

Cd-cells but with a higher internal resistance. Therefore they are useful if the discharging time is longer than one hour.

Other new developments are high energy types from ABB (sodium/sulfur) and DASA (AEGTelefunken, sodium/nickel-chloride) which are working at temperatures around 300°C. They are just leaving the experimental phase and are very efficient, but need additional heating and isolation equipment. Small sizes are not available.

The last category is silver-zinc-accumulators. They have a very high energy density, are very expensive, and survive only a few charging cycles. Therefore they remain for special applications.

For aeronautical applications the following criteria are valid:

1) high mass related capacity
2) fast rechargeable to achieve short turnaround times
3) high discharge current ($10 \bullet I_C$) with low capacity reducing factor
4) position independent mounting
5) safe against acid leakage in case of a crash

The best compromise for the size needed is the nickel-cadmium-accumulator (see Table 3).

The mass per energy content of such a battery is around 22kg/kWh. This has to be compared to ordinary fuel with 0.05kg/kWh (in (1) the fuel had 13 kWh and weights 0,7 kg). Nevertheless one should keep in mind that the efficiency of a combustion engine is much poorer (around 30%) and that for long endurance a certain amount of fuel has to be carried.

5. ENGINE CONTROL AND ENERGY MANAGEMENT SYSTEM

The control device has to fulfill two different demands. First it must give the possibility to operate the engine with different power settings and second it must have the possibility to operate the solar cells at its maximum power point to gain highest possible output.

The use of brushless electrical engines requires a more complicate system but in principle the specifications are as follows:

efficiency: 98% weight: 0.5 to 2 kg/kW

6. ELECTRICAL ENGINES

Because of the very limited available energy high efficiency has to be achieved over the whole range. The second very important point is the high power/mass ratio.

The required power is the main selection criterion, because some types of engines are only available for some power ranges. For a power demand of around 1 to 5 kW brushless motors are best for efficiency over a wider power range although their control is complicated. The biggest available engine with a resonable mass/power ratio is a special designed three-phase-current motor for electrical vehicles with 6 kW continuous

battery type	lead acid	nickel/ cadmium	silver zinc	nickel/ hydrid	sodium/ nickel chloride	sodium/ sulfur
mass/energy [kg/kWh]	25 ...33	20 ...28	10 ...14	19	8	8
charge/ discharge cycles		1,000...2,000	50...200	500	500...1,000	500...1,000
max. discharge current	$10 \bullet I_C$	$20 \bullet I_C$	$10 \bullet I_C$	$3 \bullet I_C$	???	???
capacity reducing factor	0.45 at $10 \bullet I_C$	0.85...0.76 at $10...20 \bullet I_C$	???	???	???	>0.9 (?) at $10 \bullet I_C$
recharging time	10-14h	min. 0.5-1h	10-14h	1-2h	???	min. 0.5h (?)
price factor	1	2...4	20	5	20...30	20...30
remarks			for space applications			
available	yes	yes	yes	yes	???	???

TABLE 3. Summary of different battery types (I_c = rated discharge current according to the capacity C).

Engine Type	DC-engine	AC-engine	AC-engine	permanent DC	brushless DC-engine	DC with rare-earth magnets
normal use	industry	industry	electrical powered vehicles	radio controlled aircrafts	machine tools	radio controlled competition aircrafts
mass/power ratio [kg/kW]	7...10	7...10	3...4	1...2,5	2...3.5	0.6
efficiency [%]	80...85	80...85	80...85	50...70	80...90	60...75
rmp	2,000...3,000	1,400...3,000	15,000	max. 10,000	max. 5,000	max. 15,000
power range [kW]	0.25... >50	0.25... >50	6	<1	<5	<1.5
remarks			reduction required	reduction required	reduction required	only for 20...30 sec., reduction required

TABLE 4. Summary of different electrical engine types.

	50% solar irradiance	solar cells	electronic (DC)	el. engine	gear	propeller	total values referred to nominal power	Batteries Ni/Cad
typical efficiency [%]		16	96	85	95	85	11	
typ. power per area [W/m²]	500	80	77	65	62	53	53	
typ. mass per area [g/m²]		1500						
typ. mass per power [kg/kW]		19	1	3	1	2	25	22 kg/kWh
typ. requested area [m²/kW]							19	

TABLE 5. Summary of transmission chain.

power and a mass of 19 kg. This even allows the construction of small man-carrying airships with electrical propulsion systems.

7. PROPELLER

The optimization of propellers cannnot be explained in a few words. We could use a software (3) to calculate a propeller following the minimum induced loss theory, or get a quick approximation from (4).

An example for a small aircraft shows, that for a required thrust of 80N at 14 m/s one needs at least a diameter of 2.0 m to have the chance to reach an efficiency of 85%. And this is the minimum which can be satisfying. Therefore it is very important to take the integration of such a big propeller into account while designing an electrical powered aircraft.

Furthermore, the big propeller has to rotate slowly. For most lightweight electrical engines a gear will be necessary to reduce the speed to around 1,000 rpm. This means additional weight and loss of total efficiency. Good planetary gears or belt drives have efficiencies around 95% which is, in the end, much better than using fast rotating small propellers with only 65% efficiency.

8. SUMMARY

Table 5 should give an overview of the whole transmission chain. The mentioned figures were the basis for the following design calculations of such an aircraft. In this case power means propeller power (thrust X velocity).

9. AIRCRAFT DESIGN

With the above given figures one has to try to design an aircraft concept with a wing area big enough to integrate the required solar cells to produce the energy for horizontal flight. Preliminary calculations have shown that a high aspect ratio and a big wing area are important. This led to a high wingspan (min. 20 m) in order to reduce the induced drag. The results of detailed calculations with variable masses for the propulsion unit and the structure depending on the wing area and the required power shows the following:

- an increase of wing span with constant wing area results in a higher "admis-

wingarea	20 m²
aspect ratio	25
wingspan	22,4 m
average chord	0,892 m
tailplane area	2,1 m²
wing loading	13,5 kg/m²
solarcell area	18,8 m²
takeoff mass	240 kg
stall speed	11 m/s
	28 m/s
never exceeding speed	38 m/s
dimensioning speed	44 m/s
max. endurance without solar radiation (full charged batteries)	40 min
max. range without solar radiation (full charged batteries)	34 km
time to charge empty batteries (irradiation 500 W/m²)	45 min
max. climb	2,1 m/s
min. sink	0,36 m/s
required power for horizontal flight (n=0,7)	1400 W
required thrust for horizontal flight	82 N
at a speed of	12 m/s
best gliding ratio	39
at a speed of	16 m/s

TABLE 6. Aircraft dimensions and performance datas.

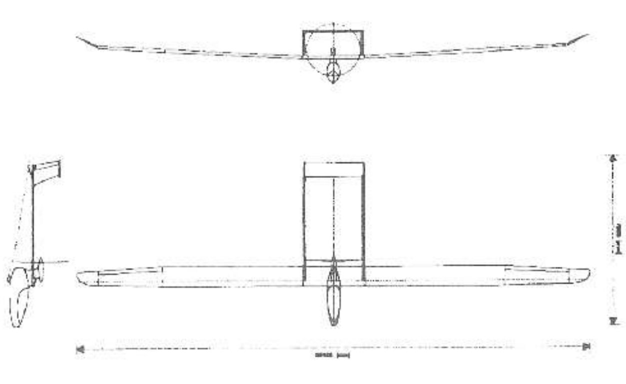

FIGURE 5. Geometry of Archeopterix.

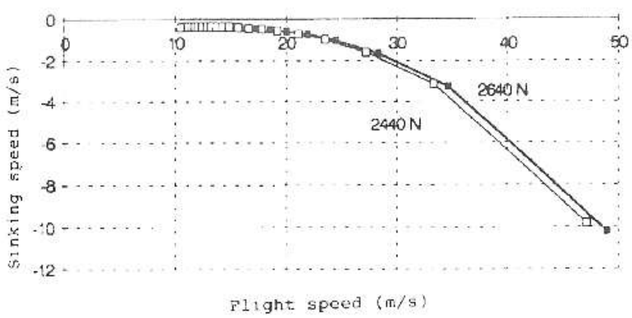

FIGURE 6. Gliding polar Archeopterix.

sible" structural mass.

- at the same time the gliding performance is getting better
- at the same wing span the glide ratio improves if the aspect ratio is increased
- simultaneously, the required power decreases but the available solar power too, due to the decreasing wing area
- the decline of the solar power predominates; therefore it makes no sense to build very high aspect ratios
- the wing area has to be around 20 m^2

The wing span was fixed to 22.4m and the wing area to 20 m^2. This resulted in an aspect ratio of 25. The design is shown in Table 6 and Figure 5 and the calculated performance in Figures 6 and 7.

The remaining question is whether it is possible to reach a structural mass of 100 to 120 kg while achieving reasonable structural strength.

10. STRUCTURAL DESIGN

Up to now structural calculations have been done only for the wing. For fuselage and tailplane unit only estimations are avialable.

For the wing design not only the loading

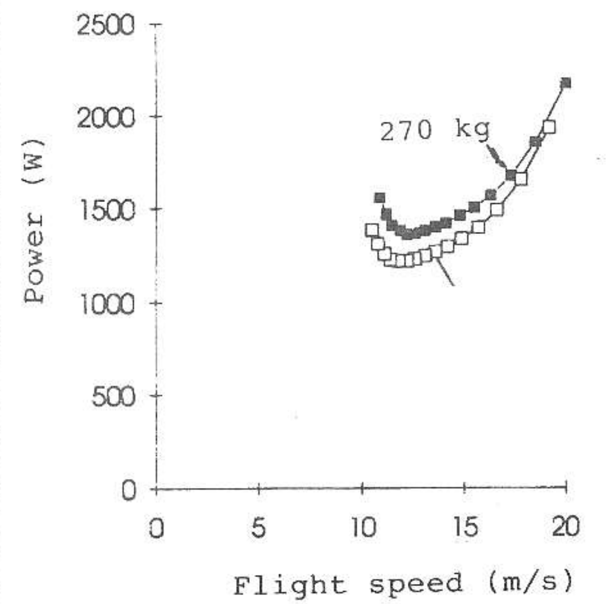

FIGURE 7. Required power for horizontal flight.

requirements for ultralight aircraft (+4 and -29) but additionally the gust loadings following JAR22 were taken into account.

The takeoff weight will be between 240 and 270 kg. For the wing design the higher takeoff mass is critical because the mass is added in the fuselage (heavier pilot) and not in the wing.

Additionally, ground loads and maneuver loads were calculated. For all in-flight load cases an elliptical lift distribution was used, which is a good approximation because of the high aspect ratio. The envelope over the maximum loads for each section of the wing was used for the dimensioning of the structure.

The construction of the wing is equivalent to a normal

one half of the wing:						
	spar:	top spar:	4.55 kg			
		bottom spar:	4.55 kg			
		web:	3.8 kg			
		connection:	2.5 kg	15.4 kg		
	wingshell:			19.9 kg		
	root:			3.0 kg		
	additional ribs:			0.5 kg		
	push rods, div.			1.7 kg	40.5 kg	
wing:						81.0 kg
fuselage:						16.0 kg
tailplane unit:						16.0 kg
	engine, gear, propeller:			10.0 kg		
	batteries:			24.0 kg		
	solar cells:			19.0 kg	53.0 kg	
propulsion unit:						53.0 kg
security system (parchute) and instrumentation						16.0 kg
empty weight:						182.0 kg

TABLE 7. Estimated mass analysis.

fiber reinforced sailplane wing with the exception of the integrated solar cells in the upper surface. The wing has to be built out of carbon fiber. The symmetrical spar could carry the whole bending forces, the shell the torsion moments. The web is only loaded by shear forces due to bending and torsion.

The estimated mass analysis is shown in Table 7.

11. CONCLUSION

It is possible today to combine available components to get a solar powered propulsion system for a lightweight sailplane and to design such a sailplane strong enough for rough air conditions and reasonable payloads. This is a big improvement compared to the solar powered predecessors ten years ago.

But undoubtfully such a glider will not lead to sudden revolution in general aviation. On the one hand it will be expensive (at least double the price of a modern open class glider) and on the other hand the glide ratio of arround 40 at a speed of only 60 km/h is not very satisfying for today's glider pilots.

The biggest advantages will result out of new developments in the field of solar powered propulsion systems, lightweight and flexible integration of solar cells and new design concepts for lightweight structural components. These could have a remarkable influence for the application of solar cells in a wide range of new fields.

12. ACKNOWLEDGEMENT

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