HUMAN FLIGHT WITH LIGHT

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1. SUMMARY

The publication "SOLAR POWERED PROPULSION SYSTEMS" (presented at the "1. International Airship Conference in Stuttgart 1993") dealt with the possibilities and limitations of solar powered flying with special reference to the use of such propulsion systems for airships, this paper shows the latest developments in solar cell integration, battery technology and electrical engines as it is integrated in the University of Stuttgart's solar powered motorglider icaré 2 XXL.

The propeller design is described. Power management, wire technology, engine philosophy and the decision whether or not to use gearing are discussed. The selection of a suitable battery system is treated in detail. Future possibilities in battery technology are mentioned. New integration technologies for solar cells will be presented and the optimisation of the integrated design will be discussed. Last, but not least, some aspects of the safety and monitoring systems are given.

This technology is accessible for use in future piloted solar powered aircrafts. The paper is amended to provide the designer with the required data of a propulsion system in the power range which is required for small aircrafts.

The prototype of the proposed propulsion system has been granted preliminary certifica-

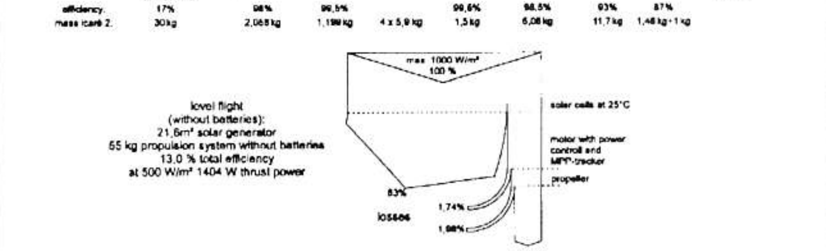
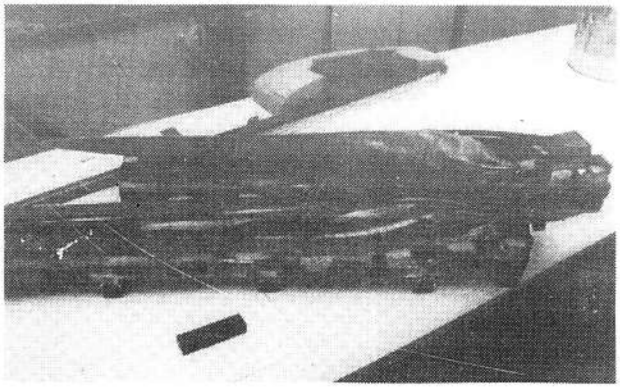


Figure 1. Energy flow in propulsion system.



Technical data:

manufacturer:	University of Stuttgart, Institut Für Aero- und Gasdynamik (Calculation, moulds) Institut für Flugzeugbau (construction, manufacturing) Institut für Statik und Dynamik (dynamic modelling)	
number of blades:	2	
diameter:	2,4 m	
blade axis:	52,5 mm	
max. chord:	125 mm	
design rotational speed:	600 U/min	
	takeoff	level flight
power:	12 kW	1,6 kW
revolutions:	1200 1/min	600 1/min
efficiency (calculated):	75 % (15,5 m/s)	87,5 %
mass:		

bladenr.	mass	residual
1	740 g	263 g
2	740 g	263 g
3	752 g	266 g
4	754 g	266 g
5	740 g	263 g
6	740 g	263 g

centrifugal force (real mass distribution):	4736 N	1184 N

Figure 2. Icaré 2-propeller (photo O. Ronsdorf).

tion from the LBA (German airworthiness authority) for use together with the motorglider icaré 2.

2 . INTRODUCTION

Following the development of a solar-powered airship "LOTTE" at the Institute for Statics and Dynamics of Aerospace Structures, the Faculty of Aerospace Engineering of the University of Stuttgart decided to take part in the Berblinger Competition 1996. The challenge was the development of a piloted solar-powered motorglider with self-launching capability and practical applicability, which is powered exclusively by solar energy. This aircraft called "icaré 2 XXL" was built in the Institute of Aircraft Construction with the assistance of all faculty institutes from 1994 until May 1996. It made its maiden flight on May 22nd, 1996 and won the Berblinger Competition on July, 7th.

One major subject was the development of the propulsion system. The difficulty becomes obvious, if one compares the energy content of one kilogram of NickelCadmium-Batteries with that of fuel. NiCd-batteries have a specific mass of more than 20 kg/kWh and fuel has only 0.086 kg/kWh. Nevertheless electrical propulsion systems can make sense, if the efficiency of all components is optimised. If the basic energy consumption could be delivered from solar cells, peak values can be provided from the batteries. Than the whole system could be more efficient particularly for long time operations.

3. PROPULSION SYSTEM

3.1 A Brief Overview

The solar irradiance is collected from the photovoltaic cells and transformed into electrical energy. The maximum-power-point-tracker adjusts the amount of energy taken from the solar generator in such a way, that the maximum power is delivered. This power is either directly consumed by the engine or used to charge the batteries. The motor control is situated behind the main spar of the fin and uses two aluminium plates integrated in the fin surface for cooling. The engine, which is placed above the rudder, is connected with four copper-cables.

3.2 Propeller

The propeller is calculated to deliver 90 N thrust for level flight (TAS 13 m/s) and 570 N for climb (same TAS). It is designed following the blade element theory and is optimised for solar powered level flight *111*. The blades are foldable and have variable pitch. A spring reduces the opening shock. Six blades are manufactured so far. They are selected to give three pairs of blades with equal masses.

The residual mass was weighed at 920 mm (relative to the blade axis). The calculated blade angles for climb and level flight are shown in the following diagrams. It is obvious, that a variable pitch is very useful to increase the propeller efficiency in changing environmental circumstances, i. e. for different irradiance.

3.3 Variable Pitch Hub

To vary the pitch and to fold the blades a special hub was designed.

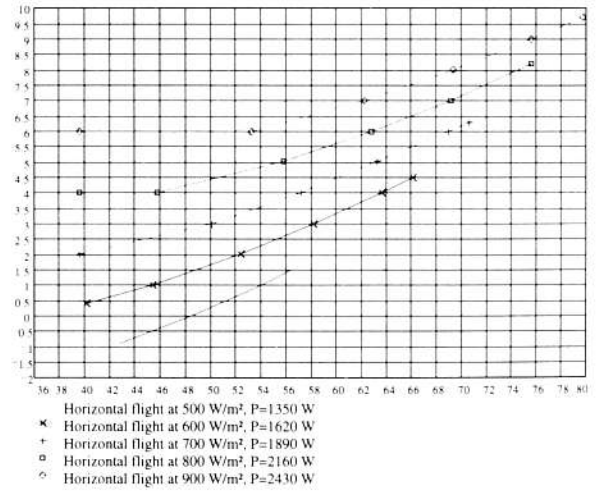


Figure 3. Calculated optimum pitch curve for level flight (pitch [°] over TAS [km/h] at 600 revs/min) (Jürgen Arnold).

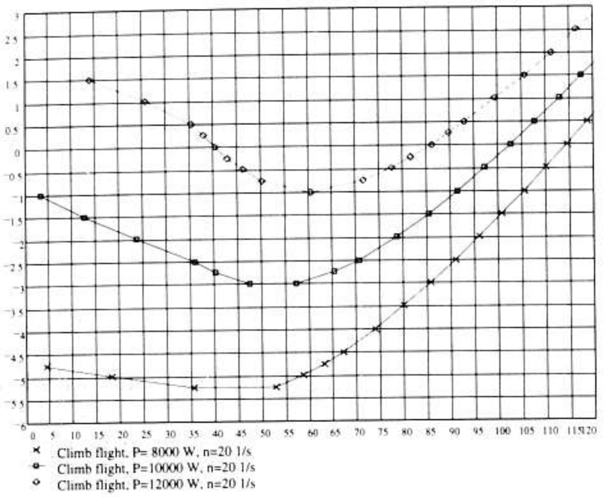


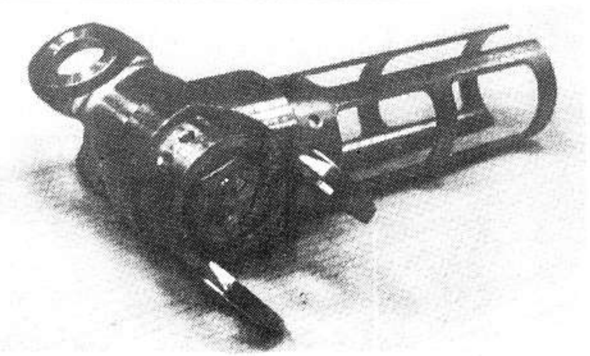
Figure 4.. Calculated optimum pitch curve for level flight pitch [°] over TAS [km/h] at 1200 revs/min) (Jürgen Arnold).

3.4 Engine

A new type of electrical motor was developed following a patent of Prof. Weh at the University of Braunschweig. It is called a "Transversal Flux Engine" since the winding goes in circumferential direction. The magnets are located in the rotor. If the electrical current is switched on, the rotor moves to the next iron yoke. If there are two rotors on one shaft which are shifted half the angle of the poles, both windings have to be switched on alternatively to make the rotor rotate. The main advantages of this system are the small required active masses (copper, iron, magnets) to produce the required magnetic field and the great power range with very high efficiency.

Bigger transversal-flux-engines are reaching power densities of 1.9 kW/kg and efficiencies of 97% already (for electric cars). Smaller units are less efficient, since the percentage of the air gaps in the magnetic system is bigger and therefore the losses are higher.

Experiments have shown, that the internal temperatures never reaches critical limits within the operational periods (5 min climb, 30 min level flight). 10 different limits have been measured on the test bed.



Technical data:	
manufacturer:	University of Stuttgart, Institut für Luftfahrtantriebe, fischerwerke Waldachtal/Tumlingen
mass:	1,0 kg
required sector:	-5,5° to 10°
possible sector:	-8° to 12°

Figure 5. Icaré 2 variable pitch hub (photo O. Ronsdorf).

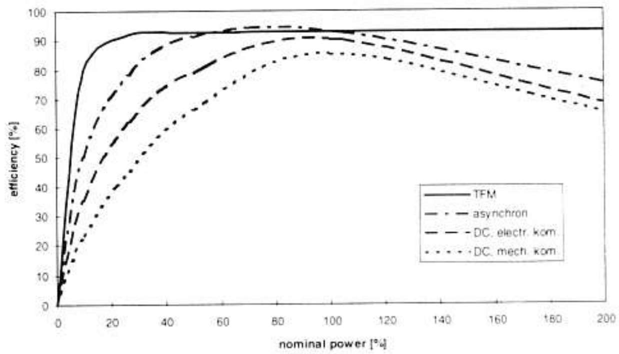
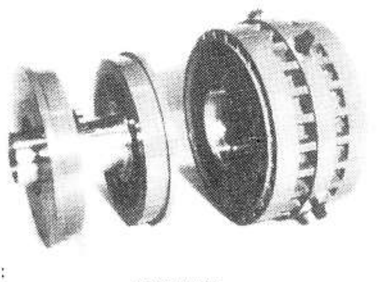


Figure 6. Efficiency of different electrical engines (qualitative).

3.5 Inverter

The inverter produces the alternating electrical fields in both circumferential windings. Therefore it has eight MOSFET-equipped power switches, four for each engine phase. The MOSFET's are riveted to aluminium plates, which are integrated on both sides of the fin surface. Temperature sensors monitor each phase.

During optimisation of the power control, one has to consider the trade-off between mass, volume and control power for a great number of parallel MOSFET's on the one hand and the reduction of losses created from the drain to source on resistance. The commutation happens through alternated shutting of switch 1 and 4



Technical data:		
name:	TFM 12kW	
manufacturer:	University of Braunschweig, Institut für elektrische Maschinen und Antriebe	
number of poles:	24	
mass:	11,7 kg	
engine diameter:	Ø 214 mm	
engine length without shaft:	120 mm	
shaft diameter:	Ø 50 mm	
operational temperature:	-40°C to 120°C	
	takeoff	level flight
power:	12 kW at 1200 U/min	1,6 kW at 600 U/min
efficiency:	93%	92%
torque:	95,5 Nm	25,5 Nm
frequency of current:	440 Hz	240 Hz
frequency of torque-oscillation:	1760 Hz	960 Hz
torque oscillation:	0.8 to 1.2 of torque	

Figure 7. Icaré 2-engine (photo IEM TUBS).

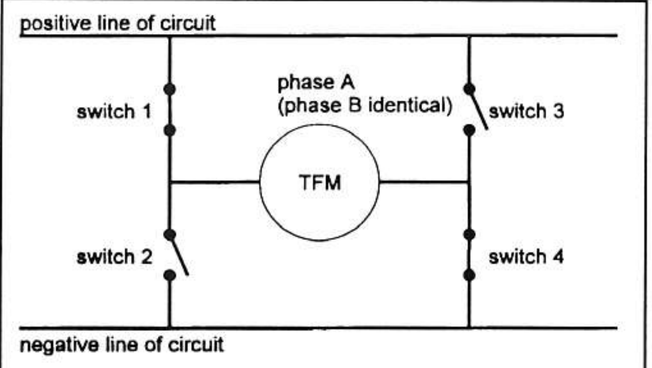
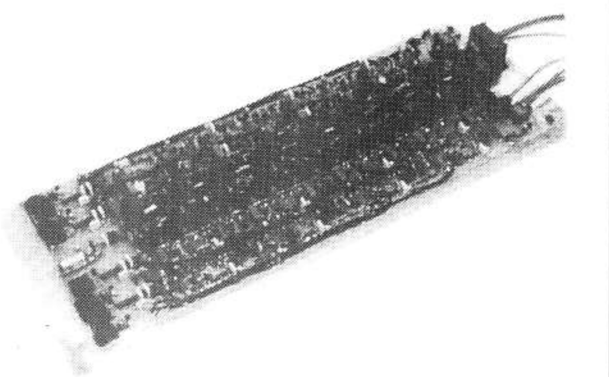


Figure 8. Circuit diagram of icaré 2 inverter.



Technical data:

name:	MOSFET-Wechselrichter 12/1,6kW-TFM		
manufacturer:	University of Braunschweig, Institut für elektrische Maschinen und Antriebe		
number of phases:	2 (right side A, left side B)		
tact frequency:	5 kHz		
maximum apparent power:	18 kVA		
	takeoff	**level flight**	
power output:	12 kW	1,6 kW	
voltage:	103 V	150 V	
output current:	180 A	50 A	(max. value, pulsed
efficiency (measured):	98,3 %	98,5 %	
mass:	5,26 kg		
size:	220 mm x 600 mm x 50 mm (including cooling plate)		
operating temperature:	0°C to 70°C (at the cooling body)		
allowable accelerations:	5g for condensators and MOSFETs		

Figure 9. Inverter of icaré 2 (one phase) (photo IEM TUBS).

and switch 2 and 3. If power is switched there are always two switches activated.

3.6 Inverter control

The inverter control is on a separate platine, mounted in the fin above the inverters. It produces the control signals for the inverter depending on the pole position and the provides the power supply.

Technical data:

name:	Wechselrichtersteuerung
manufacturers:	University of Braunschweig, Institut für elektrische Maschinen und Antriebe
mass:	525 g
inverter cable:	307 g (incl. plug)
size:	170 mm x 160 mm x 65 mm (including switching power supply)
operating temperature:	0°C to 70°C

3.7 Feeder lines

For connection between battery and inverter, PVC-insulated aluminium-cables with a cross section of 25 mm^2 are used. Aluminium has double specific resistance compared to copper but only one third of the density. Therefore aluminium cables are the better solution for weight relevant problems.

The calculation for the takeoff case (12 kW, 250 s) results in a temperature increase of 65 K (without cooling through convection and radiation!). This is acceptable for the PVC-insulation.

Technical data:

name:	PVC-insulated aluminium-cable	
manufacturer:	Badenwerke	
cross section:	25 mm^2	
mass:	106 g/m (weighed)	
length (battery - inverter)	6,9 m	
	takeoff	level flight
power:	12 kW	1,6 kW
losses through cable resistance:	2,2 %	0,12 %
temp. increase:	63,6 K	7,7 K

3.8 Battery

A great deal of expenditure was invested in the search for a suitable energy storage, since a clever selection of this component is a very strong way to influence the overall efficiency of the propulsion system.

The given task for the competition requires a high discharge current. Therefore several actual battery systems [Table 1] were compared concerning their energy and power density.

Discharging in four minutes implies, that the discharge current is 15 CA (CA: capacity related discharge current; 15 CA means discharge within 1/15 hour). Table 1 shows, that only three storage systems allow the fast discharge rates which are required (HRLAB, AgO/Zn, NiCd), even though some systems have higher energy densities. The High-Rate Lead-Acid-batteries have very good values, but they will not be obtainable until 1997, therefore they are not considered any further herein.

To evaluate the power density, a discharge time must be prescribed and a suitable constant discharge current has to be defined. The voltage is monitored during discharge and the average is calculated. Constant discharge current multiplied with average voltage is then related to the mass to give the power density. It is very important, that the current is not too high. Otherwise the battery looses its typical characteristics. If power and energy density are determined for the same discharge current, both values can be plotted in the so called RAGONE-Plot.

The tests are concentrated on a discharge time of 270s and a maximum battery mass of 25 kg. This results in the

battery system	max. current I_c [A]	power density [W/kg]	energy density [Wh/kg]	cycles	DM/kWh	DM/takeoff	abbreviation
High-Rate Lead-Acid Battery	700	5000	40	500	?	?	HRLAB
Lithium-Swing-System	4.5	370	115	1000	40000	30	LION
Sodium/Nickelchloride	1	80	100	1000	?	?	NaNiCl
Sodium/Sulfur	1.5	150	102	1500	?	?	NaS
Nickel/Cadmium	25	800	52	500	3600	5.4	NiCd
Nickel/Metalhydrid	11	350	80	1000	10800	8.1	NiMH
Nickel/Hydrogen	10	500	70	2000	?	?	NiH2
Silver/Metalhydrid	10	600	110	400	?	?	AgMH
Silver/Zinc	25	2500	170	50	35000	525	AgO/Zn
Zinc/Bromine	1.5	110	75	?	?	?	ZnBr?
cost per takeoff related to a installed energy of [kWh]				0.75			

Table 1. Types of batteries considered (B. Goltz).

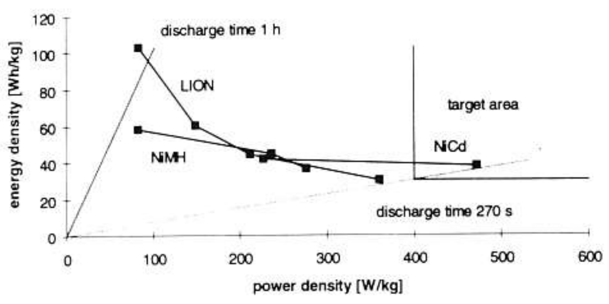


Figure 10. Ragone-Plot available battery systems (B. Goltz).

target area shown in the upper right corner of Fig. 10. Now the difficulty is to find a system with the required high power density <u>in combination</u> with a suitable energy density.

Additionally the possible number of cycles is an important criteria for everyday use.

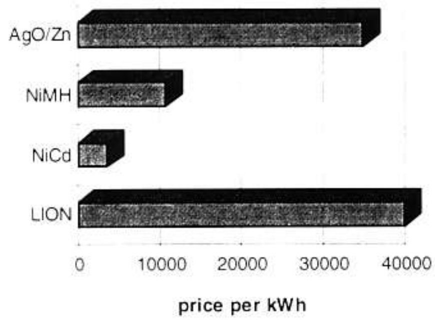


Figure 11. Costs of Different battery systems [currency: DM].

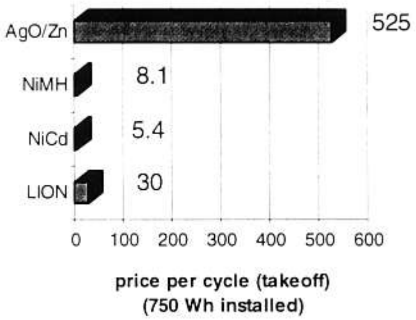
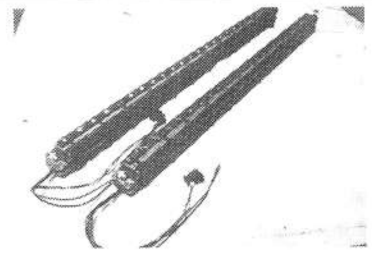


Figure 11. Costs per takeoff with different battery systems [currency: DM].

These considerations lead to the decision to use NiCd-cells for icaré, since it will not be used only for a single record flight but for intensive testing and multiple competition flights. Several different NiCd-cells have been tested and the final selection for string currents of more than 22,5 A were the SANYO N-SCRC-cells with 1700 mAh. 384 of those cells are soldered together in four packs with 96 cells.

The cells were selected to have the same capacity (same discharge time) at 20 A discharge current. These times varied between 360 and 370 seconds until 1 V was reached. This corresponds to a capacity of 2000 mAh even at this high load.



Technical data:

name:	SANYO N-1700SCRC(SP)
manufacturer:	SANYO
nominal voltage per cell:	1,2 V
nominal capacity per cell:	1,7 Ah
number of cells per string:	96, 4 times 24 cells inline soldered
number of parallel strings:	4
mass:	5,9 kg (one completed string)
average discharge voltage:	1,06 V/cell
end of charge voltage:	1,70 V/cell
discharge current (takeoff):	100 A (25 A each string)
operating temperature:	0°C to 80°C

Figure 13. Icaré 2 battery packs (photo O. Ronsdorf).

3.9 Battery management

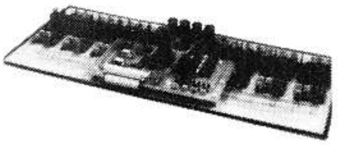
The charging and discharging of the batteries has to be supervised to give information about the actual energy content for the pilot and to prevent the batteries from overloading or deep discharging. It is installed within the fuselage in the vicinity of the battery packs.

Technical data:

name:	Batteriemanager
manufacturer:	University of Braunschweig, Institut für elektrische Maschinen und Antriebe
mass:	1199 g
size:	250 mm x 260 mm x 90 mm
operating temperature:	0°C to 70°C

3.10 Maximum-Power-Point- (MPP-) Tracker

The solar generator has one optimum point, where the product of voltage and current reaches its maximum. To enable it to work at this point, the gathered power has to be controlled depending on the actual irradiance. Since the orientation of the solar cells on



Technical data:

name:	Maximum-Power-Point-Tracker
manufacturer:	University of Braunschweig, Institut für elektrische Maschinen und Antriebe
control:	microcontroller
number of independent strings:	8
max. voltage:	250 V (MOSFETs)
voltage at MPP:	157,7 V
max. permissible current per string:	4 A (poorer efficiency)
current output (effective value):	10.7 A
max. efficiency:	98% at 1,6 kW total power
adjustment time:	< 1 sec
mass:	1700 g (2058 g with CRP-frame)
connection with fuselage:	90 g
size:	600 mm x 270 mm x 80 mm
operating temperature:	0°C to 70°C

Figure 14. Icaré 2 MPP-Tracker (photo IEM TUBS).

wings and sailplane differs very much, the whole generator is divided into eight independent strings. Each of them has his one MPP-Tracker.

3.11 Solar generator

Solar cells are integrated in the wing and sailplane structure. The generator is devided into panels, which are glued onto the wing surface after the structure was finished and which could be removed in case of a damage.

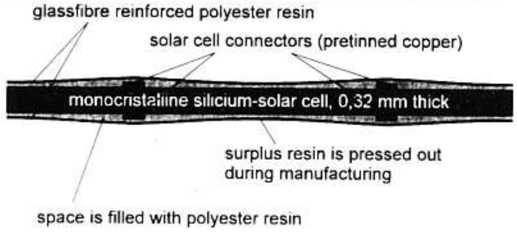


Figure 15. Integration of icaré 2 solar cells.

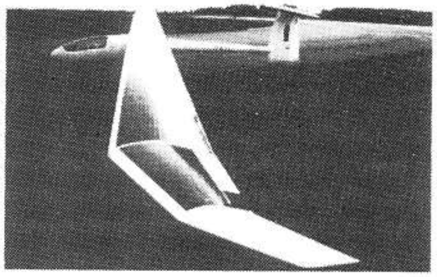


Figure 16. Icaré 2 solar generator (photo O. Ronsdorf).

The selection of the solar cells depends on the efficiency, mass (thickness), size of the cells, size of the cell connectors and required thickness for the integration. For example there are cells for space applications which are very thin but smaller in size. This reduces the weight but at the same time the degree of covering diminishes. Similar considerations have to be made to select the optimum size of the cell connectors. If they are to wide, they cover to much of the cell surface, if they are to thick, the amount of required resin to fill the space is to big, if they are too small, their electrical resistance causes excessive losses.

technical data:	
name:	monocristalline silicium solar cells
manufacturer:	ASE, Heilbronn
integration:	Gochermann Solartechnik, Wedel
integration method:	laminated between glasfibre reinforced polyester
number of independent strings:	8
cells per string:	360
generator area:	$360 \cdot 0{,}05m \cdot 0{,}05m \cdot 2$ strings $= 1{,}8$ m^2
	$360 \cdot 0{,}10m \cdot 0{,}05m \cdot 1$string $= 1{,}8$ m^2
	$360 \cdot 0{,}10m \cdot 0{,}10m \cdot 5$stringe $= 18{,}0$ m^2
	total: $= 21{,}6$ m^2
connector size:	pretinned copper 1 mm x 0,15 mm
max. efficiency:	16,2 % at 25°C (integrated, at main sea level)
max. output voltage:	216 V (without load)
voltage output at MPP:	160 V
max. current output:	3,45 A (one string with 10x10cm^2 cells)
max. power output:	600 W (one string with 10x10cm^2 cells)
max. power output:	3600 W (generator)
mass (weighed):	1300 g/m^2 (including integration)
operating temperature:	0°C to 80°C (polyester raisin)

3.12 Safety systems

The following safety devices, monitoring and display systems are installed:

- a key operated main switch disconnects through relays the solar generator and each battery pack from the main circuit
- a control systems switches all electronic components in the right order all generator strings are protected by bypass-diodes.
- solar generator strings are switched off by software control, if the output voltage drops down. This prevents the batteries from being discharge through the generator.
- temperature monitoring of the solar generator (and the wing structure underneath) with warning function and display for the pilot
- melting fuses for each generator string
- melting fuses against short cuts on the battery packs
- temperature monitoring of the batteries with warning function for the pilot
- temperature monitoring of the engine and the inverter with warning function and display for the pilot
- additional information displayed for the pilot are engine power input, revolutions, voltage and current in main circuit, capacity of the batteries and solar generator output. All data is recorded for later evaluation.

4. OPERATIONAL EXPERIENCES

Until the end of August, 1996, icaré has made 52 flights with more than 42 hours total flight time. After several ground tests, the propulsion system was in operator in 25 flights for 4 hours and 34 minutes. The aircraft performed 19 self-launches. Since the "Flight Instrument for solar Powered Sailplanes - FLIPS" is not capable for continuous data collection so far, all following information is collected by dictating machine. Therefore not enough data for a statistical evaluation could be collected. However the operational experiences collected so far are:

Propeller: for slow rotating articulated rested propellers the cone angle can reach considerable values due to the small centrifugal forces. In the case of the icaré 2 propeller this was deteriorated by the very lightweight blades. To have sufficient clearance from the rudder, the shaft has to be lengthened.

The windmilling of the propeller is so strong, that the blades do not fold due to the remaining centrifugal forces if the engine is switched of. A mechanical shaft brake will be installed shortly.

Engine: The employed NEODYM-magnets are susceptible to corrosion. Since the engine is very difficult to disassemble, no visible inspection is possible. Therefore it is essential that the engine is kept dry.

Inverter: Unlike the arrangement in the present icaré-system, it is highly recommended, that all electronic subsystems have a common earth. Otherwise insulation faults could cause different electric potentials with unpredictable effects.

All logical control circuits should be "off" at low voltage (0V) and "on" at high voltage (5V).

Batteries: The use of NiCd-cells seems to be the right decission. Average climb after takeoff is 1.8 m/s up to 250 m without additional sun and up to 370 m with solar irradiance. But it is essential that the batteries are discharged entirely after usage. Just before takeoff they should be charged rapidly. This means that a initial charging current of about 8 A (for our cells) is required that should be decreased when the voltage rises.

The most efficient strategy during climb is, to reduce the power setting, when the voltage drops below 1V/cell. Than the fresh batteries are very high loaded and the load decreases when they get weaker. At 0.7V/cell the engine should be switched off to prevent the cells from deep discharge.

The batteries reached temperatures up to 40°C during solar charge on the ground and up to 62°C during the following takeoff at an environmental temperatur of 20°C with a cooling systems that supplies the battery-compartment with an airstream with 1//4 of the IAS.

Battery management: Several flights showed, that the capacity integration algorithm implemented on the battery management calculates the "discharged" (=0%) and "charged" (=100%) condition very precisely.

MPP-Tracker: The control algorithm is fast enough to follow the rapid changing attitude of the aircraft. Some problems occured with MOSFET-failures that led to high voltage in the circuit.

Solar generator: There are no mechanical failures of cells, integration material or connectors due to the flexibility of the wing.

On a very sunny day (17.07.96, about noon) the generator temperature reached a maximum value of 64°C at a air temperature of 19°C. In flight, this drops quickly to values about 4°C above the air temperature (22°C generator at 18°C air in 250 m above ground). The supporting structure (wingspar) stays about 4°C beneath the generator. Therefore it seems to be adequate to design the structures for temperatures of 80°C (hottest day in JAR 22.1047c with 38°C plus 40°C). Suitable resin systems and temper processes have to be used.

No adverse reaction against any cleaning or other material which has contact with the generator so far is reported.

5. COMPARISON WITH THE SOLARPOWERED AIRSHIP "LOTTE"

This chapter compares the actual icaré propulsion system with the planned system and with the LOTTE system. The icaré drive (fin mounted pusher) is about 6.5 kg or 13% heavier than planned. This had visible influence on the aircraft s design, since the cockpit had to be cut away and lengthend by 200 mm to cope with the shift in center of gravity. But the efficiency and therefore the area related power reaches almost the predicted value whereas the power related mass is more than 12% greater.

mass in [g]	LOTTE	icaré planned	Icaré Reality
propeller	850	2000	1480
hub	350	1000	1000
gear	624	0	0
motor	2100	10000	11700
inverter	2300	4000	6080
main wires	1000	1500	1500
battery management	auf den Akkus	500	1199
MPP-Tracker	0	1500	2058
solar generator	16560	28000	30000
total solar propulsion system	23784	48500	55017
batteries	29520	21456	23600
total electrical propulsion system	53304	69956	78617

efficiency [%]	LOTTE	icaré planned	icaré Reality
propeller	70.00%	87.50%	87.50%
gear	95.00%	100.00%	100.00%
motor	82.00%	95.00%	92.00%
inverter	90.00%	97.00%	98.50%
main wires	97.00%	99.50%	99.50%
battery management	99.00%	99.50%	99.50%
MPP-Tracker	100.00%	98.00%	98.00%
solar generator	16.00%	17.00%	17.00%
total solar propulsion system	7.54%	13.30%	13.08%
thrust power/m^2 at 500 W/m^2 irradiance	37.70	66.50	65.39
total generator area [m^2]	7.02	21	21.6
total thrust power [W]	264.67	1396.41	1412.46
area related power [W/m^2]	37.70	66.50	65.39
mass related power [W/kg]	11.13	28.79	25.67
power related mass [g/W]	89.86	34.73	38.95
nominal power [W]	733		1600
propeller revolutions [1/min]	770		600
current at nominal power [A]	10		16

Table 2. Summary icaré 2 propulsion system and comparison with LOTTE.

The comparison with the LOTTE components shows a remarkable increase in engine, inverter and solar generator mass. But the icaré system produces 1412 W thrust power out of 21.6 m^2 solarcells at 500 W/m^2 irradiance as against 265 W out of 7 m^2 with LOTTE's system. The mass of the whole icaré system without

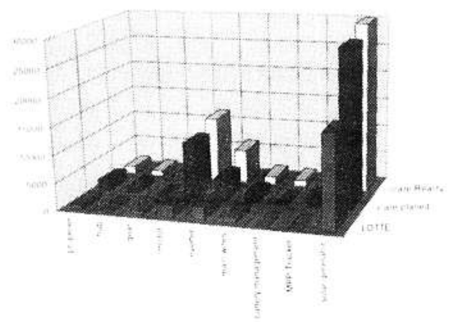


Figure 17. Comparison of the component masses of LOTTE and icaré.

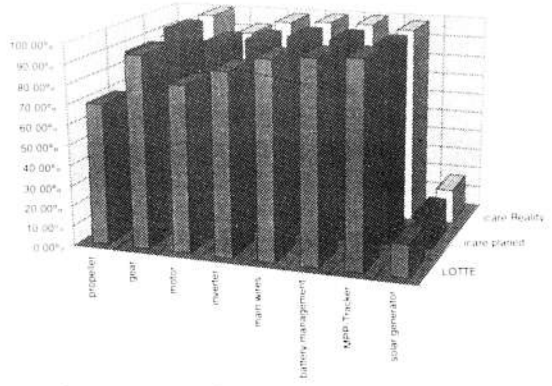


Figure 18. Comparison of the component efficiencies of LOTTE and icaré.

batteries is 55 kg. Related to the pure solar system (without batteries, since the amount of required batteries is very much dictated from the application), the specific power could be more than doubled [Table 2]. The area related power could be increased by 70 % from 37,7 W/m^2 to 65,4 W/m^2, the mass related power could be increased by 130 % from 11,13 W/kg to 38,95 W/kg. The reciprocal, the power related mass, drops from 89,9 g/W to 39 g/W.

6. CONCLUDING REMARKS

This paper gives a brief introduction into icaré's propulsion system followed by the description of some operational experiences.

The solar propulsion system reaches a nominal thrust power of about 1400 W at a total efficiency of 13% with 21.6 m^2 solar cell area and a mass of 55 kg (without batteries). Compared to the last solar powered propulsion system developed for the airship LOTTE 3b a great improvement was achieved. The area related power could be increased by 70 % to 65,4 W/m^2, the mass related power could be increased by 130 % to 38,95 W/kg. The reciprocal, the power related mass, drops to 39 g/W.

Unfortunately the prototype of this propulsion system is very expensive, but it shows a great potential for the future. So far, the operational experiences show that the engine concept completely fulfills the expectations regarding reliability and ease of maintenance. At the present time this cannot be said about the necessary electronics.

After three month continuous operation it is clear, that the batteries need a lot of servicing to reach their full capabilities. This makes the operation time consuming and demanding.

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