SOLAR POWER PROPULSION SYSTEM. TECHNOLOGICAL TRADE-OFF FOR ARIANE 5 APPLICATION

A.S. Koroteev, Yu.M. Kochetkov, V.N. Akimov, N.I. Arkhangelsky, S.A. Popov
**Keldysh Research Center*
Moscow, Russia

D. Fiot, O. Gogdet
Astrium Space Transportation
Les Mureaux, France

Abstract

This document presents results derived from previous studies realized by KeRc and funded by EADS-ST and dedicated to Solar Power Propulsion System applied to Ariane 5 upper stage. In order to push up the concept level, a first technological trade-off has been performed by KeRC replacing solar electrical arrays by devices previously investigated in AST studies:
- Fuel Cells as electrical supply
- Thermal Panels as thermal supply

1. Introduction

The desire to reduce launch and operational costs in future space transport systems has raised interest in new propulsion concepts for upper stages. Solar Power Propulsion System (SPPS) developed by the Keldysh Research Centre (KeRC) of Russia is one of these concepts. The results presented here are derived from previous studies realized by KeRc and funded by EADS-ST and dedicated to SPPS applied to Ariane 5 upper stage.
Low thrust levels are allowing a reduction of the structural index and an increase of specific impulse levels thanks to solar power, which offers a heavier payload capability with respect to present chemical stages.
This gain was associated to long transfer duration impacting slightly satellite design and commercial availability.

In order to push up the concept level, a first technological trade-off has been performed by KeRC replacing solar electrical arrays by devices previously investigated in AST studies:
- Fuel Cells as electrical supply
- Thermal Panels as thermal supply

SPPS variant with fuel cells is leading to thermal accumulator removal and SPPS restriction to propulsive mode n° 1 (pure cryogenic without propellant heating). SPPS variant with thermal panels is keeping all propulsive modes but is introducing batteries for electrical supply. Thermal panels proposed by KeRC in this study are based on an innovative concept, combining receiver and accumulator functions.

A LEO-GEO transfer application was chosen, considering Ariane 5 lower composite performance on low inclination LEO. Selection criteria are GEO payload mass and transfer durations.

2. Solar Power Propulsion System

The Keldysh Research Centre has suggested an original concept based on a combination of chemical and solar electric energy based on the same thruster. In this system the electric energy is obtained from the payload solar panels (see Figure 1).

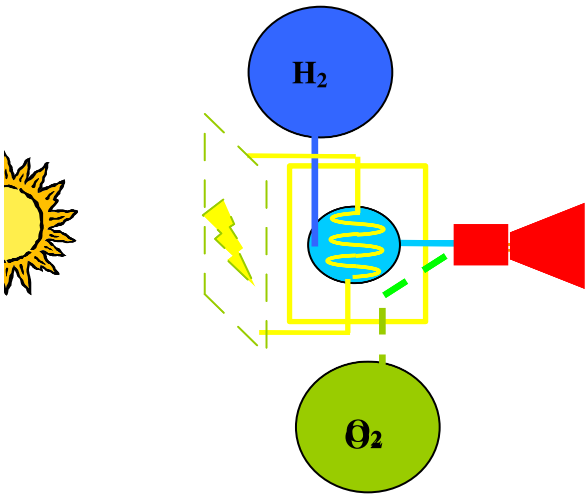


Figure 1 SPPS principle

The pure chemical mode provides a correct thrust level (several hundreds Newtons) with a specific impulse in the cryogenic class (>450 s). On the opposite, in solar thermal mode, the pure hot hydrogen (2000°K) gives a higher specific impulse (750 s) with a reduced thrust level (< 200 N).

Between these two modes, a post-combustion mode, based on hot hydrogen (1500°K) and pre-heated oxygen, provides intermediate characteristics (Isp > 500 s; T # 700 N). So the distinctive feature of SPPS concept is to offer both correct level of thrust and specific impulse and the capability to modulate these two parameters.

A great advantage of the SPPS basic concept is the use of existing technologies.

	Cryogenic mode	Post-combustion mode	Pure H2 thermal mode
Thrust (N)	350-700	150-700	100-200
Isp (s)	> 450	590-510	750
Mixture ratio	5.0	1-5	-
Temperature of H2 (°K)	20	1500	2000

Table 1. Main thruster characteristics

The hydrogen tank management is ensured by a gaseous pumping system to regulate pressure and temperature in the tank during the orbital transfer duration.

Thermal accumulation completes the SPPS concept. This additional mass provides the capability to concentrate boost periods in apogee or perigee areas. The propulsive system gets this way closer to an ideal muti-impulse system, which is energetically optimal

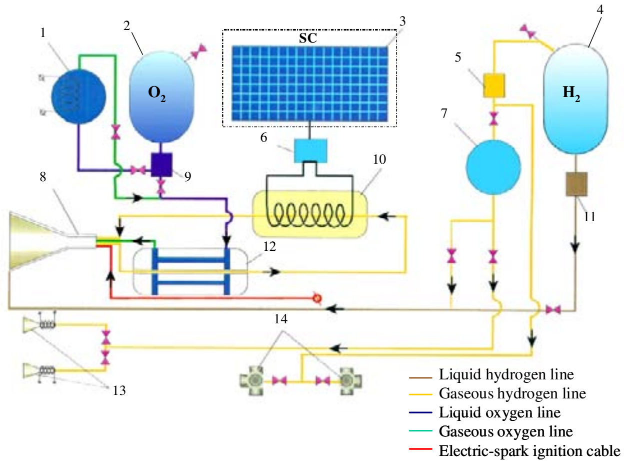


Figure 2 SPPS description

Six small gaseous hydrogen thrusters provide the attitude control. Additional resistojets are used in the last phase to increase the global system efficiency.

3. Ariane5 application

An optimization has been performed to get the well adapted SPPS and mission characteristics: trajectory, phase durations, thrust levels, propellant pressures and temperatures, propellant mass loading.

Parameter (→ GEO)	Reference ESC-B	SPPS A5 "Moderate"
Takeoff mass of stage, t	33.75	14.0
Propellant load, t	27.50	11.17
Stage inertial mass, t	6.25	2.84
Electric power, kW	–	17.8
Cruise engine thrust, kN	180	0.58 / –
Mean specific impulse (s)	464	550
Stage size: L x D (m)	- x 5.4	7.7 x 4.4
Transfer delay days	~0.5	60
Payload Mass (tons)	5.4	7.0

Table 2 A5-SPPS - moderate version – Performances

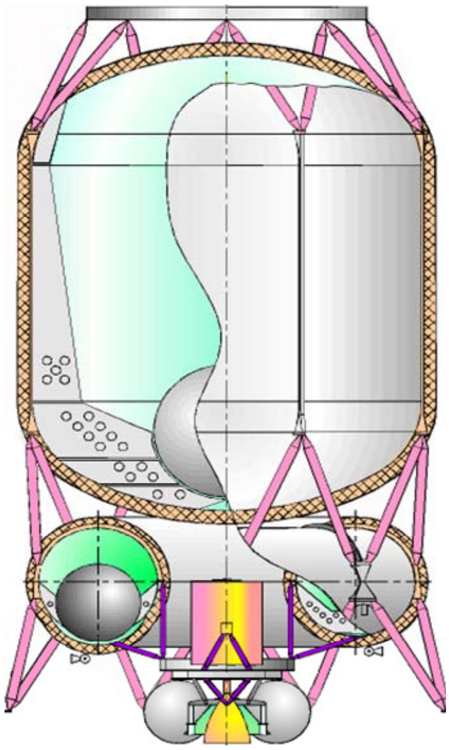


Figure 3 A5-SPPS Upper stage view

Simulations realized showed a performance increase. The order of magnitude of performance gain is around 30% with respect to Ariane 5 ESCB version

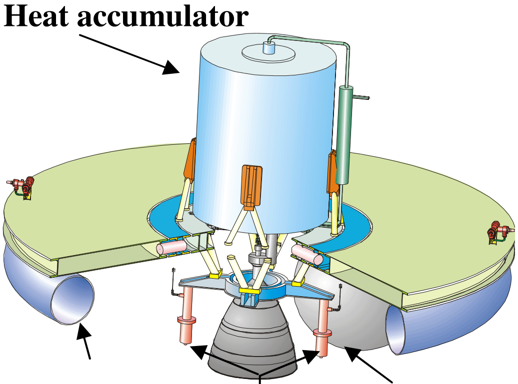


Figure 4 SPPS partial view

4. Solar array – Fuel Cell trade-off

The use of electrochemical generator (ECG) on the basis of hydrogen-oxygen fuel cells as a power source instead of solar batteries opens up some fresh opportunities:

- time of engine firings can be chosen regardless of the stay time of the stage on flight path sections sun-illuminated;
- propulsion and power systems of the stage can be made as a unified system with a common propellant storage and feed system.

Owing to these feasibilities, the makeup of SPPS can be essentially simplified, its mass decreased, and the time of SpaceCraft (SC) insertion into operating orbit can be much reduced as compared to the electrically heated SPPS.

Three types of ECG were investigated:

4.1 Fuel cells with free electrolyte

This type of FC was used on Apollo SC, scheme and characteristics are presented thereafter:

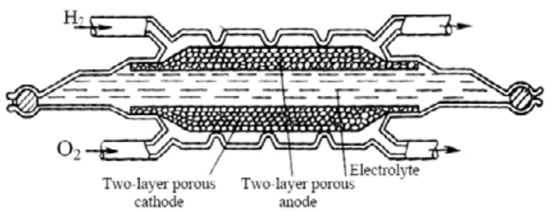


Figure 5 Free electrolyte Fuel Cell

Electric power (nominal) ……….…… 1.42 kW
ECG mass …………………………….. 111 kg
ECG specific mass ..……………….. 80 kg/kW
Specific consumption ………. . 0.4 kg/kW · h

4.2 Fuel cells with matrix membranes

This type of FC is used on Space Shuttle and Buran SC, scheme and characteristics are presented thereafter:

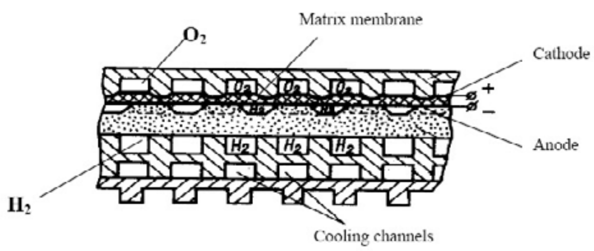


Figure 6 Matrix membrane Fuel Cell

Electric power:
– nominal …………………………….. 7 kW
– peak ………………………......... 10-12 kW
ECG mass ………………………….. 112 kg
ECG specific mass ……………….. 16 kg/kW
Specific flow rate ……..... 0.35-0.38 kg/kW⋅h

4.3 Fuel cells with ion-exchange membranes

This type of FC was proposed by General Electric for Space Shuttle SC, scheme and characteristics are presented thereafter:

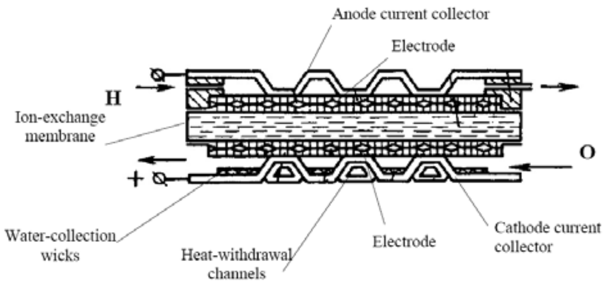


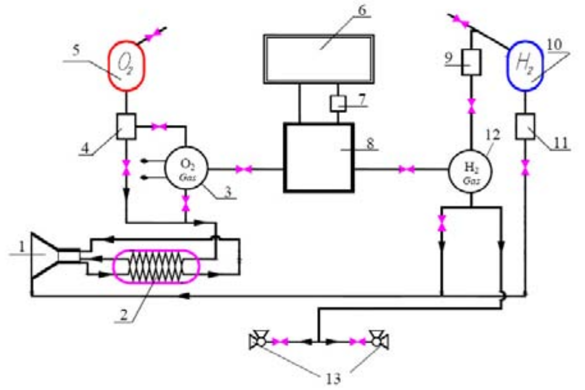
Figure 7 Ion-exchange membrane Fuel Cell

ECG power …………………………… 5 kW
ECG mass ………………………….. 56.5 kg
ECG specific mass ………………11.3 kg/kW

Pratt & Whitney fuel cells with matrix membranes used on Space Shuttle were retained for SPPS variant. The FC battery consists of 99 cells divided into three sections and connected in parallel into an electric circuit. Thus, each section incorporating 33 cells generates 2.33 kW electric power at 30 V of voltage in the maximum continuous regime.
In our case, the Ariane-5 upper stage power propulsion system calls for an ECG with electric power of 4.3 kW.

The ECG of the Ariane-5 upper stage PPS may have the following characteristics:
Kind of current ……………………..….. direct
Maximum continuous power ……..…. 4.3 kW
Voltage at the maximum power ……… 28.5 V
Pressure of FC components ……….. 0.42 MPa
Temperature of the battery ………… 82-88 °C
Consumption of propellants ..….. 0.4 kg/kW.h
ECG mass …………………………….. 70 kg
Overall dimensions … 430 × 360 × 940 mm

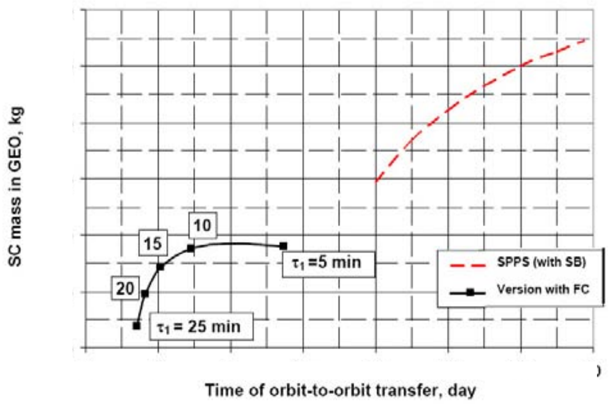
Figure 8 shows new SPPS synoptic, with Fuel Cells replacing Solar Arrays. Thermal accumulator is removed as propulsion modes with heated propellant have no more interest.



1 – cruise engine; *2* – heat-exchanger-converter of oxygen; *3* – oxygen receiver; *4* – oxygen pump; *5* – liquid oxygen tank; *6* – radiator of thermal control system; *7* – heat-carrier delivery pump; *8* – electrochemical generator; *9* – hydrogen compressor; *10* – liquid hydrogen tank; *11* – hydrogen pump; *12* – hydrogen receiver; *13* – attitude-control and stabilization engines.

Figure 8 SPPS-Fuel Cell synoptic

Comparison of Ariane 5 GEO performances is described in the Graph 1, A5-SPPS performances with Solar Batteries are shown in red (better performances for shorter cruise engine boost duration/longer transfer duration as propellant heating/ISV by Thermal Accumulator is higher for smaller mass-flow). A5-SPPS performances with Fuel Cells are shown in black for different cruise engine perigee boost duration (τ_1).



Graph 1 A5-SPPS – FC/SB comparison

It has been obtained that the variant with the power propulsion system based on fuel cells ranks below the “moderate” variant with the low-temperature electrically-heated SPPS on the basis of solar arrays in the payload mass by 250 to 650 kg. However, the variant with fuel cells has such important advantages, as:

- the duration of the GEO insertion of the spacecraft is about 4 times less (10 to 15 days against 40 to 60 days for the “moderate” variant of the electrically-heated SPPS);

- the lesser overall length of the upper stage due to the absence of the power compartment with solar arrays; the lesser length of the hydrogen tank with the hydrogen reserve lesser by ~ 1 t (mean Mixture Ratio increase after Mode 3 withdrawal).

5. Solar array – Thermal Panels trade-off

Use of solar radiation (as an external power source for preheating of propellants to raise specific impulse of the cruise engine) can be realized with thermal panels (TP). In the case, propellants are heated directly with solar heat, i.e. without intermediate phases of conversion of solar radiation power to electric, and then – to thermal power, like in the initial version of the electrically heated SPPS with its powerful solar batteries and high-temperature electric heater.
For realization of multirevolution scheme of orbit-to-orbit transfer flight, thermal panels have to repeatedly accumulate thermal power received on sun-illuminated parts of trajectory and then to transfer it to propellants in the course of multiple firings of the cruise engine. For this purpose, thermal panels are to include a heat-storing substance and heat exchanger for transfer of stored heat to propellants.

As compared to the initial version of the electrically heated SPPS, the SPPS version with thermal panels has the following advantages:

- an essentially lesser total level and differential of operating temperatures in thermal accumulator which tangibly simplifies problems of its development and provision of service life required;
- low required power of solar batteries in the upper stage.

The limiting temperature range of operation of thermal accumulator amounts to: 300 K ≤ T_{oper} ≤ 500 K which derives from the following factors:

- the maximum level of solar radiation heating of a thermal panel amounts to: T_{max} ≈ 500K;
- the scheme accepted for regeneration cooling of the cruise engine chamber defines the minimum temperature of propellants at the inlet of the thermal accumulator heat exchanger as high as T_{in} ≈ 300 K.

It is expedient to use, as a heat storing material, substances with the maximum values of specific thermal characteristics – heat capacity and heat of phase transition “melting→ crystallization”. From a great list of potential materials for heat storage, lithium was chosen:

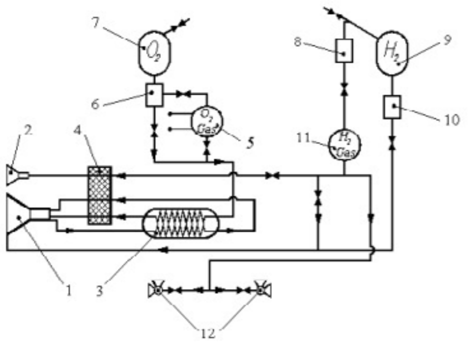
- melting point at 179 °C (452 K)
- heat of phase transition, r_m = 432 kJ/kg
- heat capacity in solid state, C= 3.3 kJ/kg·K

Due to a narrow temperature interval of operation of thermal accumulator, it has been taken that only a heat of the lithium phase transition (“melting → crystallization”) is used for heating of propellants.

The thermal panel structurally is fulfilled in the form of two parallel plates out of aluminium alloy. A room between the plates is filled in with capsules in the form of balls or long cylinders of quartz with addition agents within which lithium is positioned.

In Thermal Panels (TP) case, the Ariane-5 upper stage power propulsion system calls for an electric power of 3.6 kW.

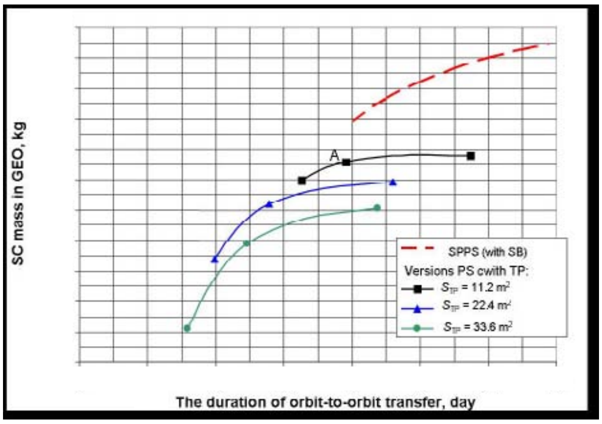
Figure 9 shows new SPPS synoptic, with Thermal Panels replacing Thermal Accumulator and Solar Arrays for propellant heating.



1 – the cruise engine; *2* – the axial gas nozzle; *3* – the oxygen converter – heat-exchanger; *4* – the thermal panel; *5* the oxygen receiver; *6* the oxygen pump; *7* the liquid oxygen tank; *8* the hydrogen compressor; *9* – the liquid hydrogen tank; *10* – the hydrogen pump; *11* – the hydrogen receiver; *12* – attitude-control and stabilization engines

Figure 9 SPPS-Thermal Panels synoptic

Comparison of Ariane 5 GEO performances is described in the Graph 2, A5-SPPS performances with Solar Batteries are shown in red and A5-SPPS performances with Thermal Panels are shown in black for different cruise engine perigee boost duration and different Thermal Panels surfaces (S_{TP}).



Graph 2 A5-SPPS – TP/SB comparison

KeRC computations have concluded that the variant with the power propulsion system based on thermal panels ranks in the payload mass below the “moderate” variant with the low-temperature electrically-heated SPPS based on solar arrays by ~ 700 kg, gaining thereat 5 to 10 days in the duration of insertion.

When compared to the variant of the power propulsion system with fuel cells, the variant with thermal panels at hand makes it possible to place into GEO approximately the same payload, but in the course of a much longer time of insertion (by a factor of about three times).

6. Conclusion

Innovative upper stage allows increasing payload mass versus high cryogenic thrust upper stage. This benefit is directly linked to transfer duration and involved some constrains at payload level: postponed availability and more robustness versus Van Allen effect.

Basic SPPS gain is interesting as soon transfer duration exceeds 30-40 days.

Use of fuel cells leads to decrease this low limit of transfer duration and has a major impact on layout (volume reduction linked to mean Mixture Ratio increase).

At the opposite, use of thermal panel offers a new alternative for increased transfer duration, but globally offers lower performance form a payload mass point of view versus moderate SSPS concept.

References

[1] F. Corberand, M. Bernasconi, P. Bravais, R. Parkinson " Solar Thermal Orbit Transfer System STOTS '' Noordwick Green Propellant – June 2001

[2] M. Calabro ''La propulsion Héliothermique'' CNES Paris - January 2002

[3] I. Gokalp, M. Calabro and H. Hollanders "Space Solar Energy: A Challenge For The European Community" Versailles - May 2002

[4] M Calabro, D Fiot, D. Estublier ''Solar Thermal propulsion'' Versailles – May 2002

[5] A.S. Koroteev, Yu.M. Kochetkov, V.N. Akimov, N.A. Arkhangelsky, S.A. Popov, D. Iranzo-Greus, O. Gogdet, D. Fiot ''Solar Power Propulsion System. Adaptation to Ariane 5 and preliminary development plan propulsion'' EUCASS Moscow – July 2005