Systems, Design &Tests Directorate

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Page 1/31

Solar Thermal Upper Stage Technologies for Future Launcher Generation Program

STOTS

Executive summary

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TABLE OF CONTENTS

List of the figures

List of the Tables

1 INTRODUCTION

1.1 CONTEXT OF THE STUDY AND GENERAL APPROACH

Solar thermal systems have been proposed since a long time (Ehricke dated 1957) to improve the performance of chemical propulsion. Best liquid engine specific impulse is limited under 500s. Solar systems were designed on the paper to almost double this performance. They would also provide a propulsion concept with

- No pollution,
- Single propellant,
- No complicated or rotating equipment
- …

The programmes presently developed in the USA as well as recent progress in the field of low-thrust propulsion, have increased, in Europe, the interest in systems using solar energy. These new propulsion concepts are investigated in order to reduce the propellant mass fraction and increase the payload mass, or use smaller launch vehicles for a given payload mass.

The objective of STOTS (**S**olar **T**hermal **O**rbit **T**ransfer **S**ystem) study is to use solar thermal propulsion in place of the upper stage of existing launchers and provide direct transfer to the final orbit.

1.2 STOTS DESCRIPTION

The solar thermal engine serves as a high-temperature heat exchanger, collecting concentrated solar radiation and transferring this energy to a propellant causing a significant specific impulse.

The solar thermal system, illustrated by Figure 1-1, consists of three interrelated subsystems, as follows:

- Subsystem in charge of collecting and focusing the sunlight for use by the system, including primary and secondary concentrators, deployment mechanism and tracking system, called Concentrator Array & Tracking System subsystem (CATS S/S);
- Subsystem in charge of converting concentrated sunlight into usable heat to produce thrust or electrical power, including the sunlight receiver, absorber and converter, heat exchanger, nozzle and engine interface structure, called Receiver Absorber Converter subsystem, or Receiver Accumulator Converter for intermittent flow system (RAC S/S);
- Subsystem in charge of storing the propellant and feeding the engine, including the liquid hydrogen cryogenic storage tank, feed lines and flow control, thermodynamic vent system and heaters, called Propellant Feed & Storage subsystem (PF&S S/S).

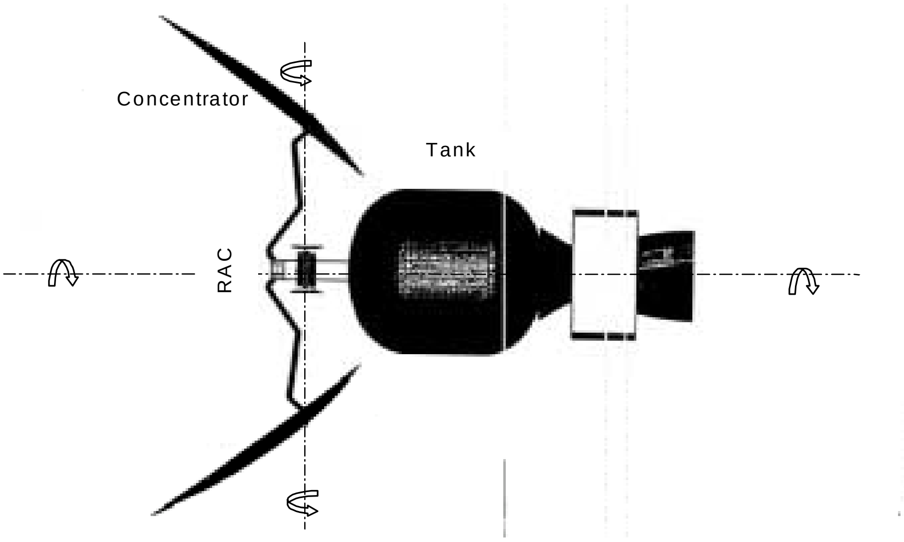


Figure 1-1 - *STOTS sub-systems description*

1.3 DIFFERENT THRUST STRATEGIES

There are **two basic types of solar thermal propulsion**.

The first approach simultaneously collects energy, transfers it to a propellant gas and produces thrust. The "continuous flow" system must perform the transfer as a spiral orbit-raising manoeuvre (see Fig. 1-2), with consequential high "gravity losses".

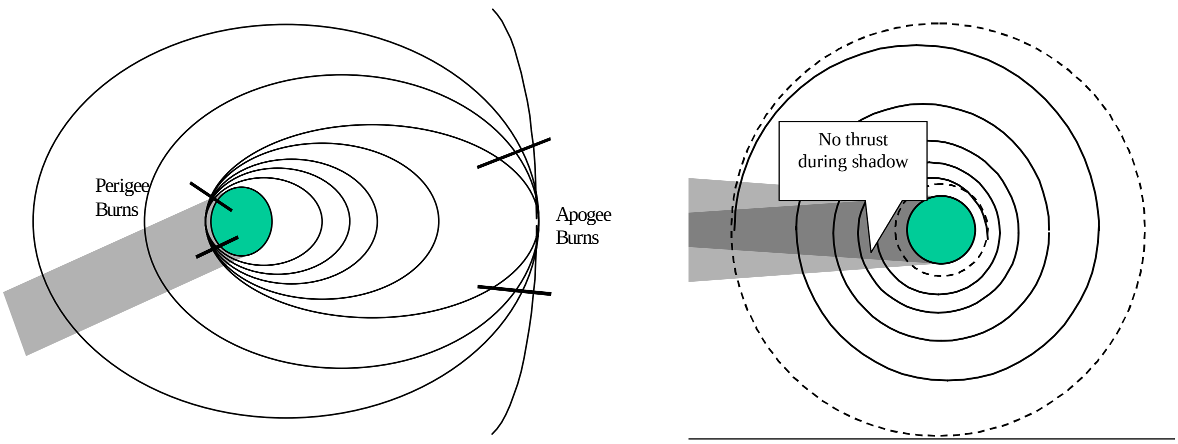


Figure 1-2 - Intermittent and "Continuous Thrust" Orbit Raising Strategy

The second approach sequentially collects energy, stores it in a thermal energy storage system and then transmits this energy to the propellant during short thrust periods (i.e. perigee & apogee boosts). In the case of "intermittent flow" the STOTS operate at higher thrusts, allowing the vehicle to perform orbital transfer manoeuvres as a series of perigee and apogee boosts with low "gravity losses" (see Fig. 1-1). The "intermittent flow" system, however, must provide additional mass in the form of thermal capacity to store the collected energy before it is used for propulsion.

1.4 STUDY LOGIC

The Study programme was composed of two phases and three activities :

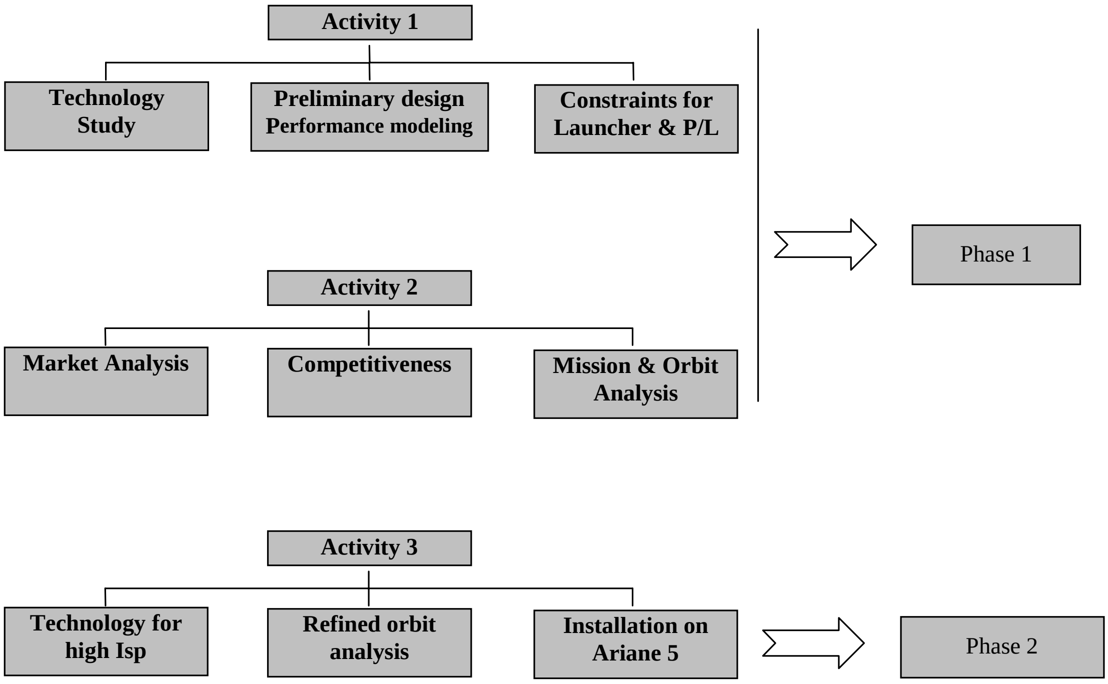


Figure 1-3 – *Study logic*

The progress of the work followed a bottom-up analysis. We start from a very wide screening of all the possible technological solutions for the three main S/S and according to the main steps described below the analysis progressively converge toward a "best" concept. We are at a pre-project step and this best concept can be defined as an answer to preliminary questions about available technologies, transfer strategy, and preferred mission.

The mains steps of the Study illustrated by figure 1.3 are recalled below:

Phase 1

- Activity 1 was essentially dedicated to technological analysis. Focus is on the availability of possible solutions. A preliminary design and modelling provided a large performance mapping of STOTS capacities. This mapping was used to identify and evaluate all the constraints induced on the launcher.

- Activity 2 –It confronts the STOTS capacities with the requirements of some representative missions. The analysis of the commercial market showed that the preferred STOTS performance range could be restrained to high ΔV missions like LEO-GEO transfer and that STOTS competitiveness required a high level of specific impulse.

Phase 2

- Activity 3 – Identification of necessary developments in Phase 1 had led to a return on technological analysis. It showed that it is possible to design a propulsion system providing the required level of temperature to the propellant (with a concentrator of sufficient concentration ratio and an heat exchanger allowing necessary temperatures) using technologies with a medium term development effort.

S BEST CONCEPT

The STOTS program was an exploratory analysis for answering a set of preliminary questions:

- Questions about the propulsion system technology
  - What are the more promising technologies or concepts ?
  - What is possible to-day with present state of art ? Tomorrow with reasonable development effort ? Later perhaps with research effort ?
- Questions about the preferred missions and transfer strategies for solar stages.
  - Is continuous or intermittent thrust the best strategy for satellite transfer from injection to final orbit ?
  - What are the more interesting missions taking account of STOTS characteristics ?

The study has progressed in a bottom-up process, from general performances offered by solar technology toward a family of "best" STOTS concepts adapted to the preferred missions.

Before detailing the conclusions, let say first that we have found very different results, depending strongly on the level of specific impulse and depending on the conditions of utilisation of STOTS ; in particular variable with the maximum acceptable duration for the mission. Maximum transfer time was assumed to be one month. This condition has been relaxed sometimes, in the case of intermittent thrusting strategy and in the case of mixed solar thermal / solar electric strategy, to see what is possible with a longer trip. In fact transfer time has, on one hand, very important consequences on performance and on the other hand it is difficult to give precisely the trip time acceptable by the client because it is linked with cost and expected profits.

The difficult problem of cost has not been forgotten but, due to the preliminary state of the analysis, first results deal with performance and we link the gain on costs with the increase of performances on a given launcher.

Anyway we have gathered sufficient knowledge about preferred missions, launchers, best transfer strategy, key technologies, and cost estimate to be able to propose some choices fixing the main options. And these choices draw the outlines of the STOTS best concept.

2.1 PREFERRED MISSIONS

Low level of thrust limits STOTS utilisation to transfers between two stable orbits.

General trends show that STOTS will be all the more interesting as the velocity increment required by the mission is increasing. A small delta-V is not favourable to high specific impulse propulsion systems.

Considering on one hand the market demand and on the other hand the high level of specific impulse offered by STOTS, the baseline mission for solar propulsion is a LEO/GEO transfer. LEO/MEO or interplanetary transfers have also been studied, but can only be considered as back-up missions.

For what concerns the launcher, the replacement of the upper stage is the good strategy. An alternative concept was initially envisaged: use the STOTS as a transfer stage attached to the spacecraft. The associated performances are very low.

2.2 MISSION CRITICAL PARAMETERS

Mission analysis confirms that a high specific impulse is necessary to get a significantly better payload than with a high performance cryogenic stage. Table below resuming the payload injected in geostationary orbit shows that it looks as if an initial charge has to be paid for the replacement of the natural upper stage by a low thrust upper stage using a low density propellant (650s would be approximately the equilibrium point where STOTS would provide the same result that A5 ESCB).

Isv	700	750	800	850	Ref (A5 ESCB)
(P/L)/(P/L)ref-1	9 %	22 %	35 %	46 %	0 %

Table 2-1- Performance for a LEO-GEO transfer – (Ariane 5 – Continuous mode thrusting).

This observation makes us fix the target for specific impulse around 800s. Requirements for the necessary technological level are derived from this objective.

It is worth quoting also that solar propulsion is the only solution to obtain an interesting performance within a 30-day transfer. We shall see below that if we want to rely on electric propulsion for a part of the transfer it is necessary to envisage trip time up to around 3 months.

2.3 KEY TECHNOLOGIES AND CRITICAL ISSUES

During many years (since Ehricke dated 1957) solar propulsion has been confined to paper studies.

The large areas and performances required by concentrators/reflectors make everyone fear the problems of vehicle integration. The design proposed by Rockwell twenty years ago R[6-1] was a first step which changed the data of the problem . “Off-axis” parabolic surfaces, allow the mirrors to acquire the sun in any position (without interference into the plume and other structures) and maintain the centre of gravity unchanged during any of the manoeuvres. The second step is now, the arrival of inflatable structures, which brought an answer to collector stowage problem and mass requirements by providing light and very compact equipment before deployment.

During ISUS program the choice between rigid expandable and inflatable solutions was not yet clear and the two solutions had been kept despite the tremendous promises of inflatables. The recent progress on this technology has changed the data of the problem and the point now seems settled. We can refer to last conclusions of Contraves in the frame of STOTS study or to the developments in progress in the U.S. concerning the SOTV programme which has adopted inflatable mirrors. R[6-2].

At the end of STOTS programme, the results of the very large technology analysis and of the mission simulations, show clearly that no "off the shelf" solution can provide competitive stage for commercial market. But we can conclude also that after a reasonable development effort (with no research level issue), it should be possible to design a solar propulsion system for all the classical missions

- with a specific impulse around 750/800s
- being compliant with the assumed specifications for the three sub-systems

Research level solutions, available only in the long term and requesting important research effort, (e.g. Fresnel lens, boron thermal energy storage material, composite tank) could improve solar system performance, in particular for what concerns intermittent mode transfer. They have been discarded for "best" concept

Main conclusions for each sub-system are detailed below. It's worth quoting that most of the issues encountered in CATS and RAC design are due to the targeted level of specific impulse(800s)

- **CATS**:

  - The main conclusion is the first line position of inflatable technology due to its packaging efficiency, very low design mass and surface quality. Industrialisation of the manufacture of standardised collectors ought to be possible, reducing their production cost well below those for any rigid component, variable geometry approach.
  - Large surface collectors are required for LEO to GEO transfers involving heavy launchers (~ 400 m² for stage initial mass around 20 tons).
  - high specific impulses induce high level of concentration ratio (~4000/8000) in order to limit radiation losses. For 800s specific impulse, very good performance, i.e. a specific power around 3 kw/kg, can be obtained with a contour error of 2 mrad and/or the use of two CPC.
  - The pointing accuracy and the collector surface integrity during the mission have still to be verified.

- **RAC**

  - Here also, key parameters and critical issues are related to the search for a high level of specific impulse.
  - In intermittent mode option, two phase materials (silicon or boron) provide a better performance than graphite, but silicon is rather adapted to a three months trip time and the availability of boron technology is very questionable. So a research phase to find new materials with high thermal capacity seems necessary.
  - In continuous mode option it is of paramount importance to dispose of material with high thermo-mechanical properties and to have an heat exchanger design allowing efficient heat transfer even for a high temperature receiver. Flat plate concept is the more efficient at low receiver temperature (Is around 700 s) ; cavity receiver has nevertheless been retained as the only solution that is capable to limit the re-radiation energy losses at high temperature (Isp around 800 s).
  - Technology issues are related to the development of a cavity heat exchanger capable of achieving a specific impulse of around 800 sec. The most important is finding and fabricating a heat exchanger material capable of operating around 2400° K that is compatible with hydrogen at that temperature. can be used for heat exchanger design.
  - Two major constraints on the heat exchanger are the minimum diameter that can be fabricated (for tubes or channels drilled in a compact receiver), and the wall-to-gas temperature drop within the heat exchanger that requires that part of the heat exchanger operates at significantly above the maximum gas temperature.
  - Several materials (carbon-carbon composite, graphite coated rhenium, refractory materials) and concepts are possible for RAC heat exchanger design. An investigation has been carried out using a model of the RAC system on cavity heat exchanger designs (composed of tubes) which meet the constraints on wall-to-gas temperature drop and tube diameter within the heat exchanger while achieving high gas temperatures and specific impulses. Taking account of

European available technology, the use of C-SiC appears to be a potential candidate. Experiments with manufacture would appear to be a priority.

- **<u>P&FS</u>**

  - LAD and TVS are absolutely necessary to avoid all the problems due to engine re-initialisation (for intermittent mode but also for eclipse occurrence during continuous mode transfer).

  - Protection of the tank for its structural cylindrical part is to be studied more in depth. Stage integration under an extra-long fairing, can be envisaged in order to save some hundreds of kg on the P/L.

  - No LAD nor TVS have ever been sized by US company for LH2 flow-rate larger than 5 g/s and the evolution of the mass of the propellant management devices as a function of the hydrogen mass flow-rate has to be ascertained for mass flow-rate exceeding 5g/s.

2.4 TRANSFER BEST STRATEGY

- Assuming a maximum transfer time of one month, continuous thrust mode appears, whatever be the mission at the notable exception of interplanetary transfer, as a simpler and more efficient solution than intermittent mode.

- Intermittent mode provides lower payload for a thirty day trip and induces much higher requirements on main propulsion system parameters: CATS area, hydrogen mass flow rate, mass of Thermal Energy Storage system.

- Between these two extreme solutions, a very small thermal energy storage accumulator could be considered in order to be able to insure sufficient thrust during eclipses periods (assuming also a higher initial orbit) . This design if successful would greatly simplify the needed tank technology by suppression of the TVS system.

All the preceding conclusions are given for the assumed transfer time around one month. If economic analysis (client demand) was less demanding, conclusions could change. A three month transfer would give a new chance to intermittent or to mixed transfer in the future.

Considering this last scenario, conclusions could be different in a few years if the present trends concerning the continuous increase of installed power onboard satellites and the correlative extension of electric thrusters to orbit transfer mission were confirmed,. The analysis of mixed transfer strategy, shows that a consistent supplementary gain in payload could result of recourse to propulsion of an all electric satellite (see best concept performance below).

In conclusion, mission analysis plus cost estimates lead to discard intermittent thrust mode for the assumed transfer time around one month.

2.5 PREFERRED LAUNCHERS

STOTS will be the more so interesting as the initial stage mass is important ; small stages are disadvantaged by the high structural index due to hydrogen low density.

The simulations performed on a set of representative launchers led to following conclusions.

- Small launchers deliver a too small payload to be interesting.
- Medium launchers that are able to deliver an upper-stage directly on a stable low earth orbit without the help of an additional stage and that perform orbit transfer in a month with moderate requirements for propulsion system are interesting for single launch.
- Heavy and very heavy launchers are similarly built, they need an additional propulsion system to reach a stable orbit and this is one of the reasons for the "initial charge" to be paid for STOTS installation on the launcher. Orbit transfer calculations also show that better results are obtained with launchers capable of high mass in low orbit. In other words launchers that rely more on upper stage to build their performance are handicapped. This is illustrated by Delta 4 M bad results. Ariane, which provides a good performance on low orbit, would be interesting for dual launch of future heavy satellites.

In the case of heavy launchers,

- Continuous thrust strategy is compulsory to limit propulsion parameters (collector area and propulsion mass flow rates) in reasonable range.
- A dual launch is a more interesting strategy for final mass might be very high for a single satellite.

****

After taking account of all the conclusions displayed above, STOTS appears to be an attractive and competitive system for GEO missions. There is at least a 35% cost saving to the advantage of solar thermal system compared to chemical propulsion launchers.

On the grounds of preceding conclusions we derived a STOTS "best" concept which can be presented under two configurations: a baseline and a simplified solution.

- The baseline is directly derived from the conclusions of the present study
- The simplified solution uses a very conservative approach and could be used for missions with no stringent requirement on transfer duration or for demonstrator flight.

2.6 BEST CONCEPT CHARACTERISTICS : BASELINE SOLUTION

The outlines of this best concept and the range of performances are illustrated below in case of STOTS installation in place of the upper stage of Ariane 5.

2.6.1 Mission/Technological choices/Performances

Mission	Transfer strategy	Technology
LEO/GEO	Continuous thrust	CATS : Inflatable structures
		RAC : Cavity concept
		P&FS : Metallic – PMD (LAD+TVS)

Taking account of the modifications induced on CATS and RAC sub-systems in case of a functioning point corresponding to 800 s of specific impulse the performance of STOTS is estimated to

P/L = 7250 kg

Providing a gain of ~ 35 % over Ariane 5 ESCB performance considering a direct injection on GEO and also to a gain of about 35% on costs

<u>Preceding results are a conservative evaluation of STP possibilities.</u>

Additional performance margin (~3.5 %) exists and could be found by optimizing the thrust break-off to reduce gravity losses adopting a quasi-continuous trusting strategy (but increasing CATS area).

A 15% provision has been applied to the mass budget during the propulsion system (CATS+RAC+P&FS) design.

Some assumptions which are sometimes used to provide performance gains, like composite tanks have been put aside, and would still increase present results - Future technologies as composite tanks, very high levels of IS (above 800s) have not been retained.

At last it is worth quoting that some advantages of STOTS have not been taken into account. which are linked to some particular features of this concept :

- No pollution,
- No combustion,
- Mono-propellant
- No rotating complicated equipment,

<u>Some points are still unsettled</u> because they have not been addressed in the frame of present study mainly dedicated to performance and technology analysis or because they are dependant of the trip time and of the evolution of technology in future years.

Points which have not been addressed are essentially all the problems dealing with GNC , operational problems, mission choices, and dependability.

The possible evolutions with technology or client requirements are essentially those linked with trip time. An increase of transfer duration would promote intermittent thrust strategy and the combined transfers using thrusters of an all electric satellite. In this last case the performance of STOTS would become particularly interesting as illustrated by the results of the CCN to STOTS initial contract. which are recalled below in the case of ARIANE 5.

	PAYLOAD (kg) **(without adaptator)**	**Transfer time** **(days)**
Mixed STP/SEP Transfer **Isp= 750s/800s**	9140/9500	90
ARIANE 5 ESCB **(GEO direct/GTO)**	5400/6370	/

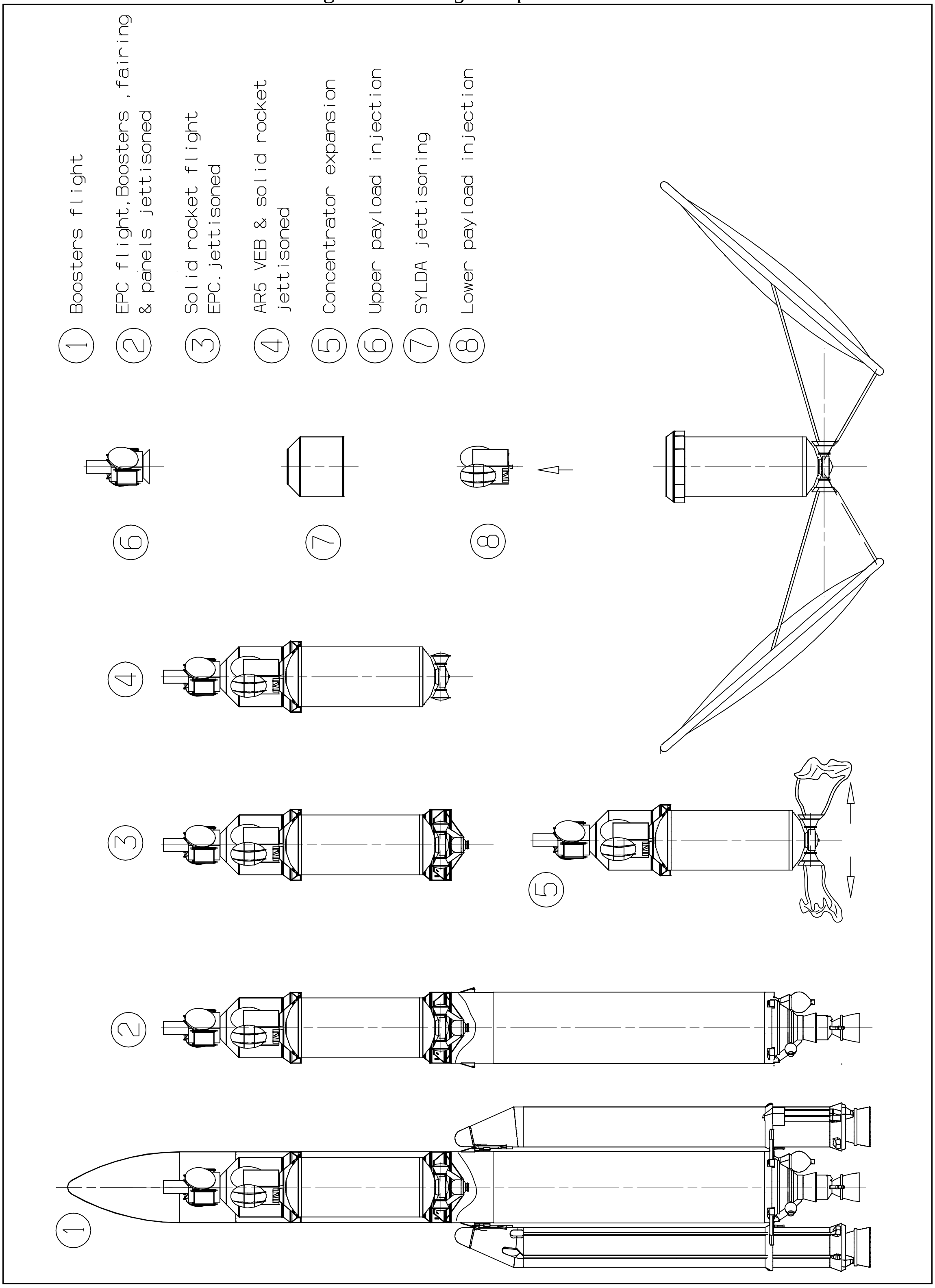
2.6.2 Description

The outlines of the STOTS presented in the figures below correspond to the following data :

- 11.5 tons of liquid hydrogen
- CATS area~400 m² , two CPC collector, Rc = 4000
- Cavity model, Isp = 750s, Tp hydrogen=2240°K
- Payload 6616 kg .

A flight sequence is first shown below to visualise the parts jettisoned during each flight phase.

Figure 2-1 – *Flight sequence*



The general architecture of the stage after A5 VEB and solid rocket jettisoning is then presented on figure 2-2 below :

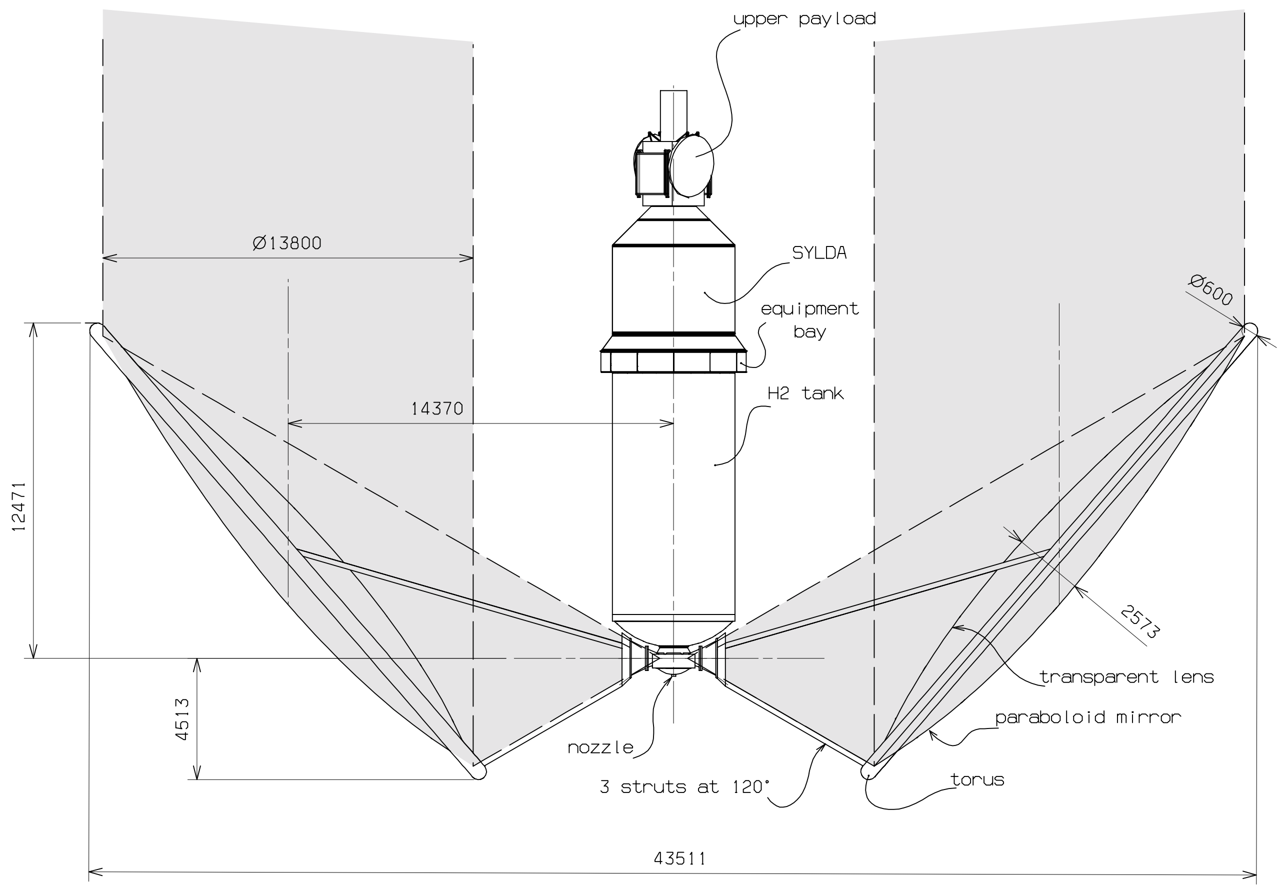


Figure 2-2 – STOTS after solid motor jettisoning and collectors deployment

On figure 2-3 STOTS additional stage is presented. It is composed of the entirely composite Ariane 5 VEB, type B (Perfo 2000 definition). A CFRP structure composed of six panels is fixed at the lower ring of the conical adapter and supports the solid grain motor. This motor is derived from an existing one developed for the upper stage of a missile

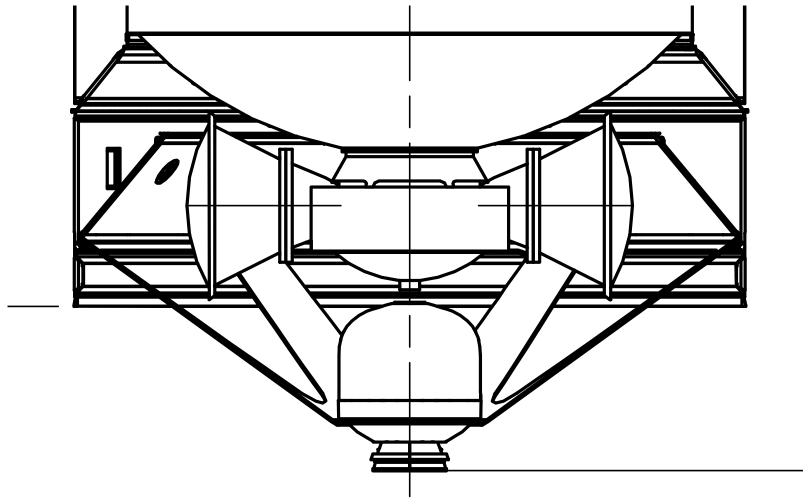


Figure 2-3– *Additional stage*

Conical boxes, used as containers for the stowed collectors, are accommodated at the outlet of secondary collectors. When the collectors are deployed, these boxes become supports on which collectors beams are attached. They are motorised in order to insure the pointing of the collector.

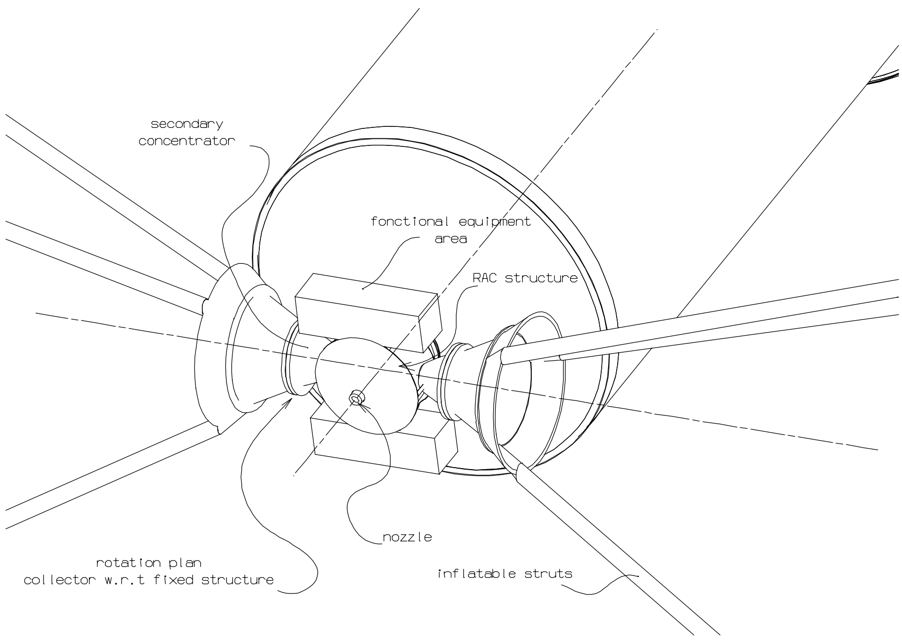


Figure 2-4- *RAC and CATS collector containers*

The mass budget is not derived from a preliminary sizing but is estimated on the basis of similarities with structures which have been analysed during preceding studies.

Dry masses are grouped together after separation instants so they can be used easily for trajectory studies.

Jettisoned with the fairing :	3347 kg
Long fairing	2747 kg
Casing + jettisoning system	600 kg
Jettisoned with the EPC :	271 kg (lower part of A5 VEB)
Jettisoned with the solid motor	1640 kg
A5 VEB	1080 kg
Motor inert mass	190 kg
Motor attaching structure	120 kg
Stage conical supporting structure	250 kg
Dry mass during STP flight	3859 kg
Sylda 5	474 kg
Forward bi-conical structure	413 kg
Equipment support plate	137 kg
Equipment and wiring	200 kg
Isolated & Equipped Tank	2507 kg
Exchanger	40 kg
Collector	88 kg

Table 2-2 – *Mass budget*

2.7 SIMPLIFIED SOLUTION

This solution could be envisaged for a demonstrator or for a mission with almost no requirement on trip time. Simplicity is searched with plate concept, a very low concentration ratio allowing to use a single stage concentrator and a low temperature RAC. The PMD system remains the only difficulty to fabricate this system.

Mission	Transfer strategy	Technology
LEO/GEO	Continuous thrust	CATS : Inflatable structures
		RAC : Plate concept
		P&FS : Metallic – PMD (LAD+TVS)

No drawing has been performed on this solution. External look remains the same as for reference case.

2.7.1 Performances

The outlines of the STOTS corresponds to the following assumptions for design :

- 12.1 tons of liquid hydrogen
- CATS area~400 m², single stage collector, Rc = 1000
- Cavity model, Isp = 700s, Tp hydrogen
- Payload 5920 kg

Recall:	A5 ESCB performances in GEO
6370 kg	(double launch in GTO)
5400 kg:	(double launch in GEO)

2.8 NEXT STEPS OF THE STUDY

The Solar Orbit Transfer Vehicle SOTV illustrate the different steps preceding the in space experiment. This flight has been prepared by successful engine ground demonstration and by extensive studies to resolve feasibility issues on concentrator and designs and on hydrogen on-orbit storage and supply systems. A fully integrated on-sun ground test should take place next year with a full scale concentrator to demonstrate the technologies necessary for a successful space flight experiment.

At the conclusion of STOTS effort we have indeed some clear conclusions about available technology, transfer strategy, best solution in relation with transfer duration.

Precise specifications can be edited to be able to begin with development work at S/S level with clear options of what is possible now, at medium term and later with research effort.

And all the elements to specify the next step of the work dealing with RCS and ground qualification of sub-systems.

Our preliminary study has shown that the interest of solar technology is obvious if sufficient effort is made on each sub-system to provide high specific impulse i.e. to develop high concentration CATS, high and compact heat exchanger and PMD equipment. It is the price to pay if we don't want to miss what should be in the future a very powerful complement to chemical propulsion first stages on future launchers.

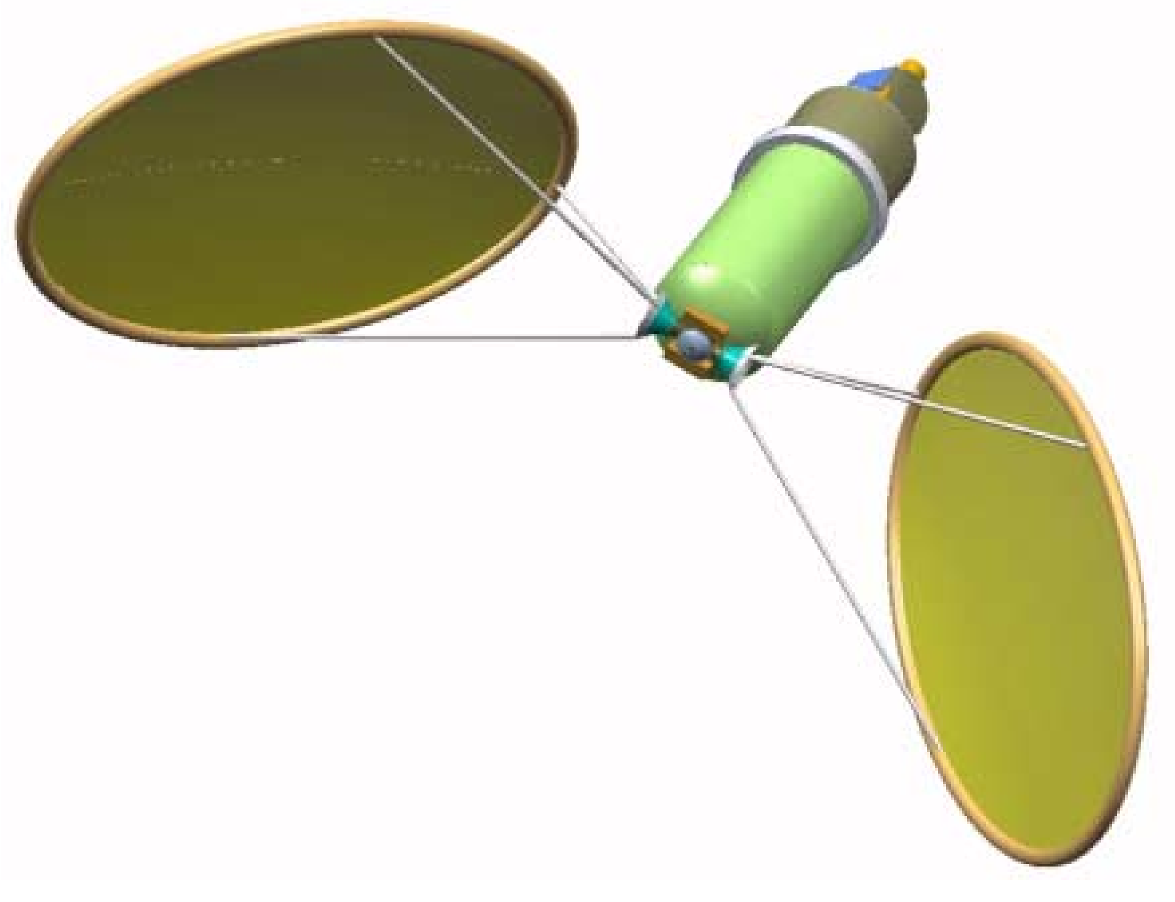


Figure 2-5 - *Flight configuration – Back sight*

3 REFERENCES

3.1 GENERAL REFERENCES (CONTRACTUAL DOCUMENTS)

[1-1] Solar-Thermal Upper-Stage Technologies for Future Launchers - Solar Thermal Orbital Transfer Stage (STOTS) – AO/1-3548/99/NL/PA

[1-2] Solar Thermal upper stage technologies for future launcher generation program – STOTS – Activity 1 – STOTS technologies and preliminary design – EADS LV – YX/PL N°132438 – October the 15th

[1-3] Solar Thermal upper stage technologies for future launcher generation program - STOTS Activity2 – Looking for STOTS best concept - YX/PL n°133596 April the 3rd 2001.

[1-4] Solar Thermal upper stage technologies for future launcher generation program - STOTS Activity3 – STOTS best concept & associated technologies- YX/PL n°134850 November the 5th 2001.

[2-1] STOTS - Concentrator Arrays Technologies – Contraves space

[2-2] STOTS – Deployment and orientation mechanisms – Contraves space

[2-3] STOTS -Technologies & preliminary STOTS designs – Receiver, Absorber & Converter - ASTRIUM -

[2-4] STOTS -"Literature survey on insulation systems"- Air Liquide

[2-5] STOTS "Literature survey on Liquid Acquisition devices and Thermodynamic Vent Systems" -Air Liquide - Bravais, M. Leroy

[2-6] STOTS “Study of the propellant feed & storage sub-system” - Air Liquide

[2-7] STOTS –Software description – Intermittent functioning - EADS LV – YX/PL n° 739/00

[3-1] Payload market and launcher status analysis - EADS LV – YX/PL N°903/00 – 30/11/2000

[3-2] STOTS - Evaluation of the constraints on the launcher derived from the STOTS implementation – EADS LV – SY/VN n° 420/00

[3-3] STOTS PROGRAM – Performance analysis of STOTS on a set of missions and launchers - Note EADS – YV/TP N°29170/CE – 1/03/2001

[3-4] STOTS -Technologies & preliminary STOTS designs – Competitiveness – ASTRIUM

[4-1] CATS Technological analysis – To Be Published

[4-2] Solar Thermal upper stage technologies for future launcher generations – STOTS – WP 3321 – Receiver, absorber & Converter – Investigations of Cavity RAC – R.C.Parkinson – ASTRIUM – 23/07/01

[4-3] STOTS program – Performance analysis of an upper stage using a mixed thrusting strategy (Solar thermal/Solar electric transfer) – YV/TP N° – 30/09/2001 – EADS-LV

[6-1] The place of Solar Thermal Rockets in Space – Selph – AFRPL – JANNAF 1981

[6-2] Solar Thermal Propulsion IHPRPT demonstration program status – AIAA 2001-3735 – 37th Joint Propulsion Conference

4 ABBREVIATIONS & ACRONYMS

ABBREVIATIONS

A	effective concentrator area
$CR = (\frac{R}{r})^2$	concentration ratio
D	diameter of collector
F	focal length
G	block factor
I	solar flux
q_{in}	Input energy flux
Q_c	Heat collected
r	receiver aperture radius
R	collector radius
R_s	solar reflectance of the concentrator mirror surface
T_r , T_a	receiver, ambient, absolute temperature
W_s	Solar power upon the concentrator
α_s	receiver's solar absorption
δ	concentrator accuracy
ε	receiver's emissivity
σ	Stefan-Boltzmann constant
σ_T	standard deviation of the image size onto the receiver
ϕ	intercept factor = $1 - \exp(\frac{-1}{2.C_r.\sigma_f^2})$, with $\sigma_f = \sigma_T / R$

ACRONYMS

BAF	Bâtiment Assemblage Final (Final Assembly Building)
BIL	Bâtiment Intégration Lanceur (Launcher Integration Building)
BOL	Beginning of Life
CATS	Collector and Transfer System (Solar Thermal)

CERs	Cost Estimating Relationships
EP	Electric Propulsion
EPC	Etage Principal Cryotechnique
EPS	Etage à Propergols Stockables
GEO	Geostationary Earth Orbit
GNC	Guidance Navigation & Control
GTO	Geostationary Transfer Orbit
IBM	Initial Boost Motor
Isp	Specific Impulse
kEUR	Thousand Euros
LAD	Liquid Acquisition device
LEO	Low Earth Orbit
MEUR	Million Euros
N/A	Not Applicable
OTV	Orbital Transfer Vehicle
P&FS	Propellant & Feed System (Solar Thermal)
PCU	Power Control Unit
P/L	Payload
RAC	Receiver, Absorber & Converter (Solar Thermal)
RCS	Reaction Control System
S/C	Spacecraft
SCA	Attitude Control System
STOTS	Solar Thermal Orbital Transfer Stage
STP	Solar Thermal Propulsion
SYLDA	Ariane Double Launch SYstem
TES	Thermal Energy Storage
VEB	Vehicle Equipment Bay