GLEX-2012.09.4.3x12520

Propulsion Technologies and Roadmap for Moon and Mars Missions

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The paper gives an overview of the European propulsion product and technologies as well as the current status of propulsion technologies planned to be developed and qualified for the Lunar-Lander Missions. A more detailed focus is set on proposed propulsion technologies for final soft and precise landing with an outlook of these technologies to be used for future exploration missions (e.g Mars sample return mission) by adaptations. In the summary and close out alternative propulsion technologies are compared and discussed.

1. INTRODUCTION

Exploration missions to Moon and Mars are only possible when adequate systems for the transportation, descent- and for some missions ascent propulsion systems are available. Most of the technologies and products were developed and qualified to fulfil the needs for transportation of commercial satellites to GTO and LEO. Therefore a wide knowledge is available for large- and small propulsion systems for launchers and spacecraft. Adaptations of these systems were used for specific scientific missions like Ulysses, NASA science Mission GALILEO, Mars Express, Venus Express, Rosetta and for re-entry demonstration missions like ARD (**A**tmospheric **Re**-entry- **D**emonstrator).

Within this paper, an overview is given of the chemical propulsion technologies available, and those to be developed in Europe for the planned exploration missions within the coming years. Currently, these propulsion systems need to be capable of:

- Transfer to the planet orbit of interest and separation of landing module (or fly-by on hyperbolic orbit).
- Transfer to the non atmospheric goal planet, descent manoeuvres (break-manoeuvre) e.g. Moon.
- A soft and precise landing on the surface.
- Ascent and rendezvous in orbit with precision docking or direct fly-back to earth
- Transfer back with re-entry into Earth's atmosphere.

The development of new technologies and their follow-on development and qualification needs a couple of years, depending on the complexity of the systems. Therefore national agencies, as well as ESA, have to react in time and to initiate the necessary development programmes of the propulsion systems required for exploration.

2. ASSUMPTIONS

In the mid-term roadmap for storable propulsion, Astrium ST investigated the need for technologies to be developed for Launchers, Human Space Flight (HSF) as well as for Science, Robotic and Exploration (SRE) applications. The focus was set on storable propellants and there application for kick-stages, upper-stage engine(s), ATV-follow on propulsion system and the Moon- and Mars mission under investigation at ESA (Lunar-Lander, ~~Lunar~~ ExoMars, and Mars sample return). Fig. 1 shows the current planned ESA Exploration Missions.

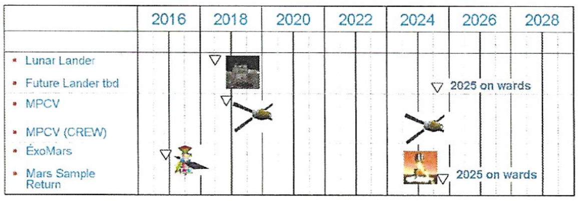

Figure 1: Europe's HSF & exploration planned missions.

The investigation was performed under several assumptions and hypotheses. The main assumptions being:

- Use as much as possible, technologies already developed and financed by ESA and/or European or national institutes /organisations.
- Short and medium term focus on unmanned missions. Long term focus (2025 and beyond) on crew ~~manned~~ missions.

Remarks:

- Due to the absence of detailed mission requirements, only a portfolio of options can be discussed.
- The use of ISS as a "base-camp" for exploration missions is not considered.
- The development of technologies shall have a positive, synergetic benefit on other ESA and commercial projects.
- A high degree of propulsion system reliability is considered essential.

3. EUROPEAN LIQUID PROPULSION SYSTEMS HERITAGE

Since the beginning of space propulsion activities in the 60ties Astrium ST is one of major player in propulsion and has demonstrated with subsystems and components for the missions its competence in propulsion.

The European propulsion industry has gathered extensive experience in propulsion systems for telecommunication programmes. Since the beginning approximately 160 systems have been built and delivered to commercial primes and Agencies.

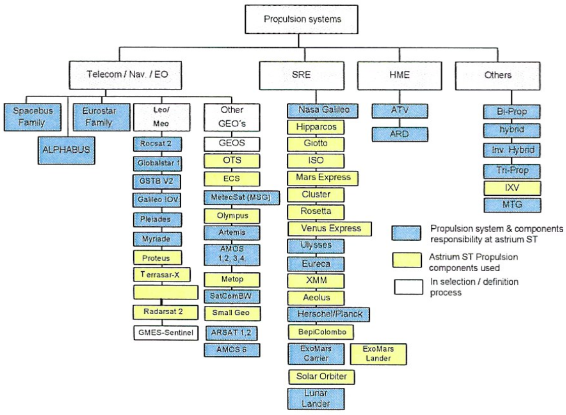

Figure 2: Liquid propulsion system heritage in Europe.

Fig 2 shows the Astrium ST contribution to propulsion subsystems as subsystem responsible (blue) and supplier of components (yellow). Unique science systems were designed, developed and and qualified based on the commercial qualified platforms (Spacebus, Eurostar). The most complex propulsion system ever built in Europe was for the Automated Transfer Vehicle (ATV). The complexity of the system was mostly driven by the requirement that ATV will be docked to the International Space Station and has therefore to fulfil all human safety, reliability and redundancy requirements~~, resulting in a 3 inhibit barrier~~.

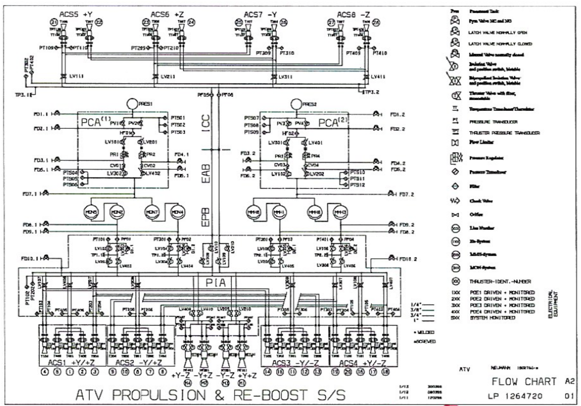

Figure 3: The ATV propulsion system. [Ref. 1]

The system comprises 28 x 220 N pulse attitude control thrusters and 4 x 500 N boost engines and incorporates three barriers (inhibits). In addition to the docking requirement, the propulsion system is able to re-boost the ISS in its nominal orbital position, as well as support the attitude control of the ISS whilst docked.

Complex tests were performed at system level in order to investigate e.g. water hammer effects and complex thruster / engine operations for the docking and the ISS re-boost operations.

~~Major headings are capitalized, underlined and centred in the column.~~

4. ASTRIUM ST PROPULSION PORTFOLIO

The Astrium ST storable propulsion portfolio is covering two different kinds of propellants,

- bi-propellant MMH/NTO, and
- monopropellant N2H4.

Figures 4 and 5 illustrate the thruster / engine portfolio. Among these products, monopropellant and bi-propellant thrusters / engines are currently in production status in different thrust classes:

1. Monopropellant thruster / engines (N2H4 decom-position with catalyst material) in development; in modification and as qualified product in production:
   - CHT 1, in production and in orbit for e.g. LEO missions and other constellation programs;
   - CHT 20, in production and in orbit on METOP;
   - CHT 400/SCA, in production and in application as roll control thrusters for Ariane 5 launch vehicle, ExoMars EDS and ;
   - CHT 2500, in demonstrator status (TRL 4). This engine has been developed with throttable capability for exploration missions.
2. Bi-propellants thruster / engines (MMH/NTO)in production or in development:
   - 10 N, 3 different version in production and in orbit as reaction control thrusters for commercial and agencies missions;
   - 22 N has been developed and is awaiting for a customer to be than qualified in accordance to the requirements;
   - 200 N, in production and in operation as reaction control thruster for ATV;*
   - 400 N, in production and in use as liquid apogee engine on commercial platforms for GTO to GEO transfer;
   - EAM 500 N, in development, a high performance LAE covering all European telecom requirements, also foreseen for MPCW (**M**ulti-**P**urpose-**C**rew **V**ehicle) the ATV follow on vehicle;†
   - Within the scope of the MTE TRP ESA identified the need for 6.0kN>1.5kN throttling. Within the ANTIOPE Astrium / ESA-GSTP examine the basics of pintle performance. In the case of the need for a larger lunar lander, that need is 24kN thrust at system level provided by 4 throttleable engines at 6kN max rated thrust. details will be given in Chapter 8.3
   - 30 kN Aestus engine, in production as upper stage engine for Ariane 5 ES version;
   - 56 kN Aestus II upper stage engine, in demonstrator status with TRL 5-6. The engine has been built and tested in cooperation with Pratt-Whitney Rocketdyne. The thrust chamber has been designed and built based on the proven Aestus heritage.

Detailed technical data of the Astrium ST product portfolio are also given in Ref. [3].

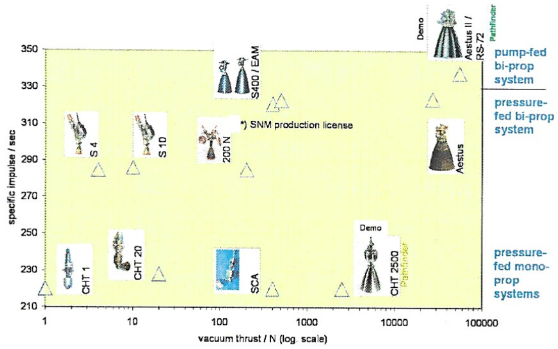

Figure 4: Astrium ST storable thruster & engine portfolio.

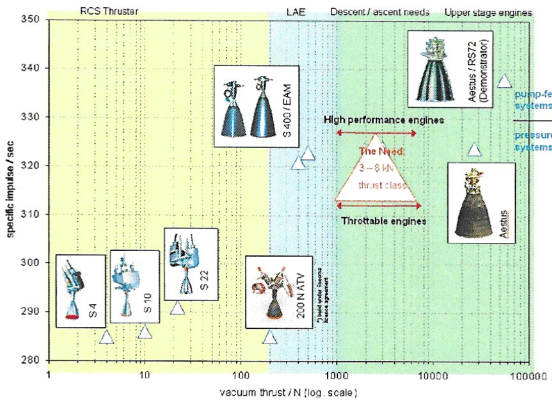

Figure 5: Bi-propellant thrusters / engine portfolio and needs.

The performance differences between bi-propellant thruster/engines in steady state operation (Isp ~ 320 s) and monopropellant fuel (Isp ~ 220s) is approx 50 %, inherently linked with the energy released by the de-composition and combustion process. This difference in terms of specific impulse may significantly impact the mass balance (payload, but also structural mass for tanks, propellants, etc) for the different missions. It is relevant to be mentioned that all spacecraft's are mass

* *200 N engines build under license agreement with Snecma.*

† *Study phase to be initiated to assess delta-development effort needed for application on ATV evolution.*

optimized. A tailored propulsion system design is mandatory to balance mass and performance.

As shown in Fig. 5, in the thrust range between 500 N up to 30 kN currently no flight worthy engine is available, and high performance engines will have a significant higher Isp-performance than throttable engines. For the development, the critical elements of any bi-propellant MMH/NTO pressure-fed engine are:

- Combustion stability;
- Thermal flux management;
- Isp - performance.

All three design aspects need to be balanced. Depending on the size of the engine, different cooling strategies may be realized. From a performance point of view, the best cooling concept for the combustion chamber is the regenerative cooling, i.e. the coolant mass flow will be fed into the cooling channels of the combustion chamber (in flow direction or vice versa) and will be finally injected into the combustion chamber, being then burned with the other propellant. Key element here is the sufficient amount of cooling fluid to prevent self decomposition of the propellant in the cooling channels. For large engines such as Aestus or Aestus II, a sufficient fuel mass flow is available to be used for regenerative cooling. For thrust levels below approx. 10 kN, also the oxidizer flow may need to be considered for regenerative cooling.

In the 500 N thrust class, the film-cooling is well established, however asking for high temperature resistant wall materials to meet high performance requirements. Further, high nozzle extension area ratios are realized to maximize performance, with typical values around ε =300 - 400.

For the nozzle extensions in this class, radiation-cooling is mainly applied, in some cases combined with film-cooling mainly necessary for the part after the throat area.

It is noted that the final engine design has to respect somehow diverging or contradicting design drivers, like

- system pressure,
- engine size/thrust class, and
- large operational range.

As a consequence,

- a high performance engine will have limited operational range (optimized to one load point),
- deep throttable range down to 8- 15% of the nom. operation range will have the disadvantage of an overall lower performance (8 - 10 %).

These aspects need to be critically considered within the pre-development and development phase for any new engine. Specific mission requirements may ask for high performance <u>and</u> throttability. These requirements are diverging, and cannot be met by a single thruster / engine design. For example the multi- ignition capability and "pulse-mode" operation of a throttable engine is in contradiction to a high performance engine.

An illustration of the different design and cost-driving factors is given in Fig. 6. For each development, the balance between high performance, deep throttability and low development effort has to be considered.

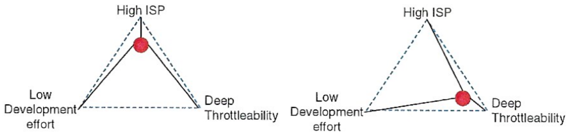

Figure 6: Correlation between low-development effort, high Isp and throttability.

Different design solutions of high performance and throttable engines are discussed in Ref. [5].

On the other hand, monopropellant engines are using a catalyst material for the chemical decomposition of N2H4. They will be mainly operated in blow-down mode from 25 bar tank pressure down to 5 bar. This type of engine has a high throttle capability, but with a 50 % lower performance compared to bi-propellant engines. The Astrium ST engine CHT 2500 N (TRL 5) was developed especially for exploration missions with landing (descent) objective.

5. AVAILABLE RE-ENTRY PROPULSION TECHNOLOGY

With the second flight V502 of the Ariane 5, Europe launched the Atmospheric Re-entry Demonstrator (ARD) capsule into near earth orbit for the re-entry demonstration. The main objective of the propulsion system was to provide the re-entry capsule with the correct position and orientation prior to entry into the atmosphere. For this task, a monopropellant propulsion system was selected.

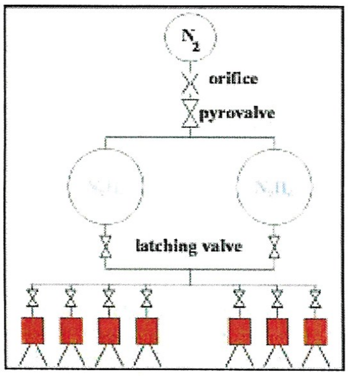

Figure 7: ARD propulsion system.

The engines used were based on the Ariane 5 SCA attitude and roll control thrusters, but having different scarfed nozzles with low area ratios [3].

The thrust level was throttled by the tank pressure, since the system was used in blow-down mode. Table 1 shows the qualification performance data and the thrust variation after re-pressurisation.

A variety of dedicated computer simulation tools were created in order to simulate as close as possible the mission.

ARD-qualification	Ps=12 bar	Ps=25 bar
Isp_{SSF}	2044 Ns/kg	2073 Ns/kg
F_{SSF}	248 N	478 N
Ibit (100ms/1000ms)	33 Ns	47 Ns
Isp (100ms/1000ms)	1976 Ns/kg	2050 Ns/kg
Rise time (100ms/1000ms)	45 ms	
Decay time (100ms/1000ms)	130 ms	

Table 1: ARD qualification performance data.

Figure 5 illustrates the complete ARD mission, which was performed successfully in 1996.

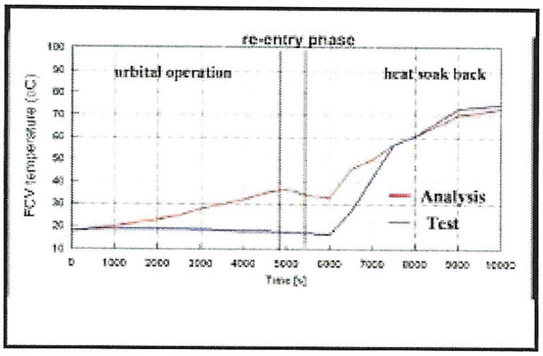

Figure 8: Flow control valve temperature versus mission time.

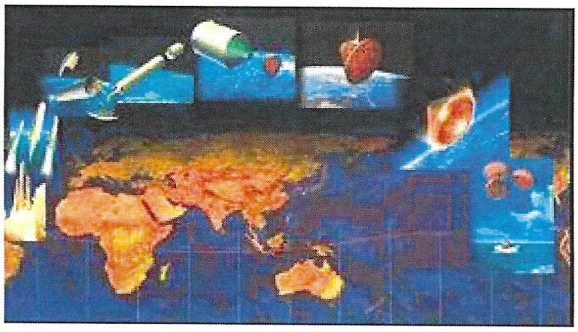

Figure **9:** ARD mission [10].

6. MISSION PROFILES

The ESA space exploration missions can be principally split into four groups:

1. ISS access including re-boost capability for ISS, man-rated mission requirements;
2. Missions to the Moon;
3. Mission to the Mars;
4. Human space flight exploration mission[‡].

The time table (Fig.1) indicates at which time Europe is planning to launch the missions. Regarding the ATV-Missions a total of 5 missions are planned. The last ATV-3 Edoardo Amaldi has docked on the ISS safely on 28.03.2012. The de-orbiting is planned for the 27.08.2012.

Table 1 show the destination, mission, the planned launch date as well as candidates for the main- and AOCS propulsion. The colored field in the table denote:

- green: available engine / thruster; and
- yellow: engine / thruster to be developed /adapted.
- red: new development is needed

Destination	Mission	Year	Main Propulsion	AOCS (pulsed)
LEO	MPCV	2018	4 x 500 N EAM (steady)	24 x 220 N 200N to be adapted
LEO	MPCV with Crew capability	2025 ff	Bi-Prop Subsystem as above plus 30-40 kN (steady)	24 x 220 N
Moon	lunar lander	2018	5 x 500 N EAM (steady) 6 x 220 N (pulsed)	16 x 22 N
Mars	ExoMars Carrier (Orbiter)	2016	1 x 400 N (LAE)	20 x 10 N
Mars	Exomars Demo-Lander	2016	3 cluster systems with 3 x 400 N CHT400 (pulsed) each (Σ= 9)	8 x 22 N CHT22
Mars	MSR/ Orbiter/ Lander/ Ascender	2025+	1500 N (steady), 12 KN (throttled), 5 kN (steady)	10N, 22 N

Table 2: Storable propulsion needs.

Up to 2025, the following missions are under consideration:

1. Access to the ISS with the ATV follow-on vehicle MPCV. The multi purpose concept shall be extended for Crew transportaion in a second development for a flight in 2025;
2. Robotic Moon missions with a Lunar Lander.
3. Robotic mission to Mars (ExoMars) in 2016 with landing on the surface (without rover mission, because this will be the passenger for a Russian mission.
4. A Mars Sample Return (MSR) mission is in planning status with a sample return to Earth mission starting in 2025.

‡ Remark: The group 4 propulsion needs for human space flight exploration missions are expected to be beyond 2025 and are therefore not discussed within this paper.

For the mission scenarios under investigation several constraining elements have to be considered. To be highlighted in view of propulsion are the launch vehicle capability (mainly Soyuz and Ariane 5, both to be launched from CSG, Kourou), the spacecraft or lander mass, and the dedicated mission objective.

The mission profiles for the MPCV will be similar to the ATV mission profile except the fact that the propulsion module will be separated from the MPCV prior to the re-entry to earth.

The descent and landing of Lunar Lander is given in Figure 2, Ref. [2].

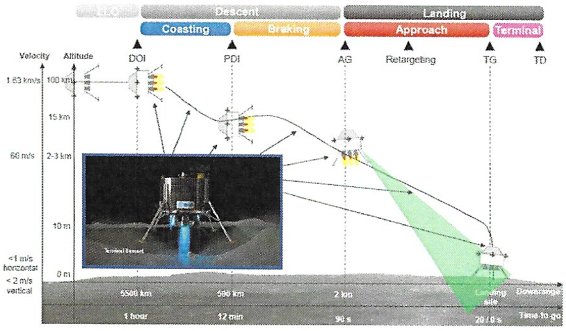

Figure 10: lunar landing phases (adopted from Ref. [2]).

The Lunar Lander mission scenario is based on a Soyuz launch from Kourou. After transfer to the Moon and some operation in the Low Lunar Orbit the landing will be performed with the coasting, braking-, and approach-phases prior touchdown of the vehicle on the Moon surface in the South Pole region. Due to the absence of any atmosphere, the total landing Δv on the Moon surface is approximately 2030 m/s. Therefore and due to the higher ISP a bi-propellant propulsion subsystem was selected. The main propulsion braking maneuver requires a 3.5 kN thrust level, and an overall final breaking phase of approx 12 minutes. The thrust level needs to be reduced during descent & landing. This will be realized by a sequential shut of the main thrusters. The additional 200/220 N engines in a pulse mode operational mode will be used to ensure a smooth transition of the sequence. In addition 22 N RCT thrusters are accommodated to be used for attitude control. Just during the contact of the first landing leg with the Moon surface the propulsion system will be completely shut off. The thruster pattern of the Lunar Lander is shown below in Figure 11.

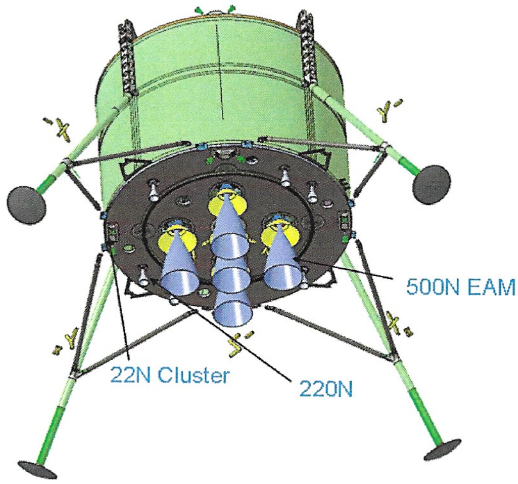

Figure 11: Lunar Lander Thruster Pattern

The engines needed for e.g. a mission to Mars are quite different, because most of the braking Δv could be achieved by atmospheric re-entry and the use of a parachute. Due to the low density of the Martian atmosphere, final deceleration has to be performed by rocket engines (NASA's Spirit & Opportunity missions used three solid rocket motors for the braking maneuver). For soft- and precise landing with a liquid propulsion system, the Δv touch-down requirement is about 40 m/s and therefore different to a Moon landing scenario.

The ExoMars landing sequence on Mars is illustrated in Fig. 5

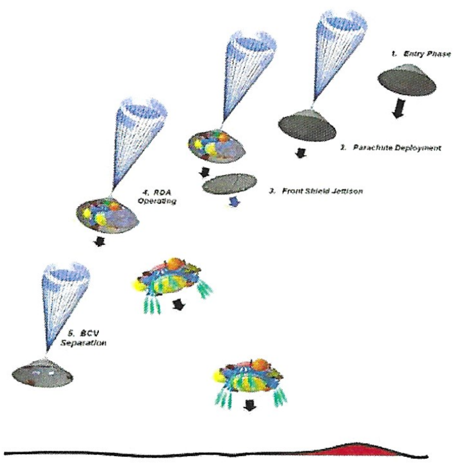

Figure 12: ExoMars descent planned mission.

The monopropellant propulsion subsystem for the ExoMars lander is under TAS (*ThalesAlenia Space*) responsibility. The design is based on 3 independent clusters each equipped with 3 x 400 N SCA-thrusters developed for the Ariane 5 EPS version. Feasibility hot firing tests have been performed due to deviating system requirements. In these tests the selection of the SCA thruster for the ExoMars landing subsystem has been demonstrated successfully. The mission requirements cover both steady state firings and pulse mode operations.

7. LAUNCH AND TRANSFER

The Lunar Lander mission will be launched from Kourou with a Soyuz-Fregat 2.1b launcher not later than 2018. The launcher will insert the Lander into a HEO orbit, from which the Lander's propulsion system will be used for entering Lunar Transfer Orbit and Lunar Orbit Insertion.

Following transfer to the Moon the Lunar Module will be inserted into a low lunar near circular orbit (at about 100 km altitude) on which preparations for landing will be performed. Final descent and landing with the subsequent soft landing will then be initiated aiming for a landing near the Lunar South Pole on the near side of the Moon.

Fig. 13 Launch into HEO with Soyuz-Fregat from Kourou

The ExoMars mission shall be launched from Kourou with a Soyuz launcher no later than 2016. The spacecraft architecture foresees a carrier where the ExoMars lander capsule is mounted on top. The capsule will be separated when the spacecraft is on its hyperbolic curve to the Mars. After separation the carrier will be injected into the Mars orbit and gets a "Mars-Orbiter".

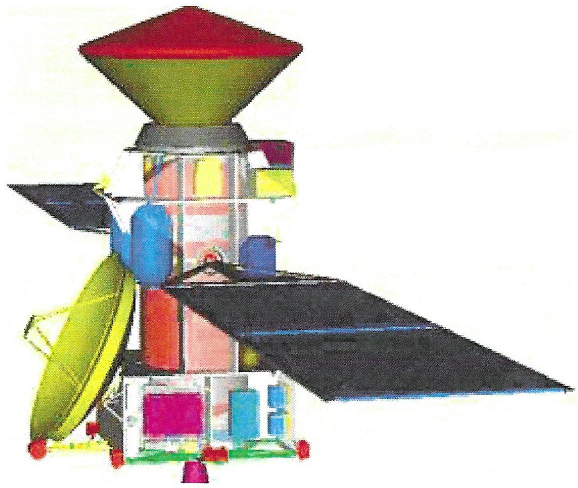

Figure 14: ExoMars carrier & EDS, Ref. [6].

8. ASTRIUM ST CURRENT DEVELOPMENTS

8. 1 Lunar Lander propulsion concept

The propulsion concept is based on three different engine types which all use MON as oxidizer and MMHas fuel:

- 5 x 500 N EAM engines for continuous thrust operation
- 6 x 220 N pulse modulated assist engines, based on ATV heritage
- 16 x 22 N ACS thrusters

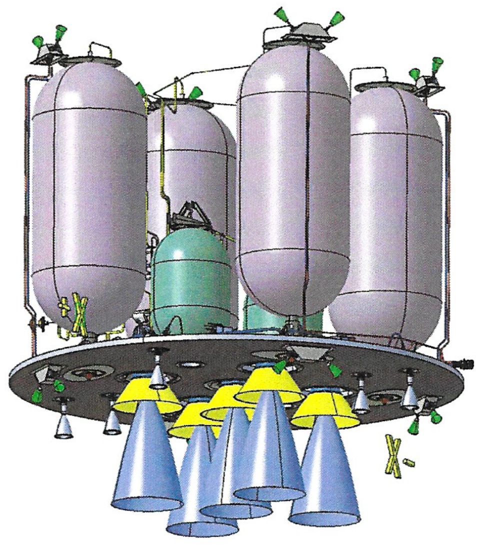

Figure 14: Lunar Lander Propulsion Subsystem

In addition of the detailed analysis of a failure tolerant design of the propulsion subsystem, the Lunar Lander B1 study will give particular focus to pressure drop and cross talk effect analysis of the engine cluster fuel sloshing analysis and mitigation techniques thermal analysis of the clustered engine concept incl. examination of the cluster plume effects.

Within the Phase B1 the following propulsion breadboard activities were performed. Objective of these activities was to mitigate the risk for key technologies needed on the Lunar Lander mission at the very beginning of the development. Therefore dedicated tests were performed aiming in more detail at the following components.

220N thruster hot firing test

The main objectives of these tests were:

- Check for low frequency instability robustness
- Performance at 1;2...3 Hz pulse mode frequencies
- Temperature characterization

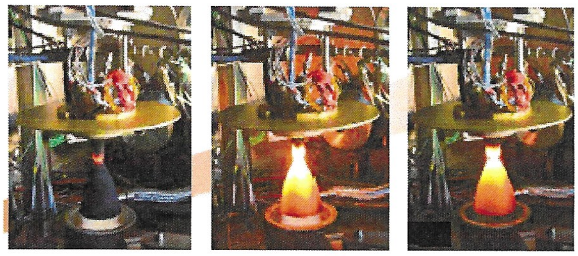

Figure 15 - hotfiring test of the 200 N Thruster

The main results of the performed test programs showed:

- smooth and stable thruster operation at reduced trimming domain;
- no indications for hard starts or LF/HF instabilities;
- no negative impact on thruster operation by changed parameters, eg reduced thruster pressure drop, reduced propellant inlet temperature;
- no signs for thermal instabilities during PMF at pulse frequencies > 1 Hz;
- pulse mode frequencies being possible without violating material constraints (frequencies of 2.0, 2.5 and 3.0 Hz with duty cycles from MIB (t_on_min = 28 ms) to DC = 50 % and n = 2000 consecutive pulses);
- smooth and uncritical thruster thermal behavior under "Lunar Lander landing and descent profile".

In consequence the 200N Thruster demonstrated excellent compliance with the needs.

Hydraulic Testing

Tests with a detailed hydraulic model of the propulsion subsystem were performed to gather the behavior of:

- Priming of the system
- Static pressure drop
- Water hammer testing
- Cross talk assessment
- Symmetry tests

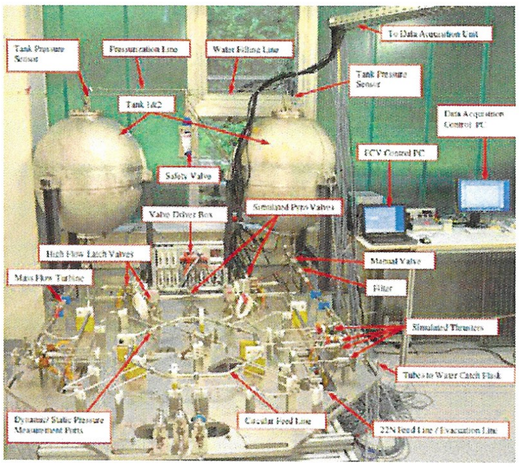

Figure 16 – Hydraulic test set-up

Status of Testing:

- The static and dynamic pressure drop measurements were performed and were in the expected range of Δp but also confirmed excellent symmetries in all thruster operational configurations.
- The thruster cross talk for the 2... 3Hz pulse frequencies were finished.
- The flight representative sequences ("Lunar Lander landing and descent profile") and the priming tests were completed
- Failure cases and margin tests performed
- Validation tests for details of modeling in progress

The test results were used for the "calibration" of the established ECOSIM model. The status of modeling and validation with test results is being presented in [9].

A further investigation was the testing of a pulse mode operation of the Astrium built 22N Thruster for the Lunar Lander application. This test campaign has successfully been performed with an all European configuration. First results are presented in [11].

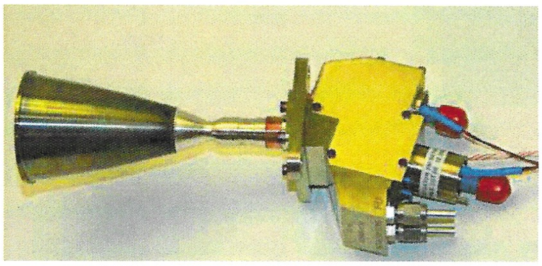

Figure 17: all European configuration of the 22 N thruster

8.2 ExoMars – Astrium ST participation

Entry –**D**escent and landing **S**ystem (EDS)

As pointed out above the EDS is using 3 independent but identical cluster subsystems. Astrium is in charge of delivery of the 400 N monopropellant thruster. Therefore feasibility tests were successfully performed in accordance with the requirements. In addition a change of the connection from screwed version to welded titanium version was introduced.

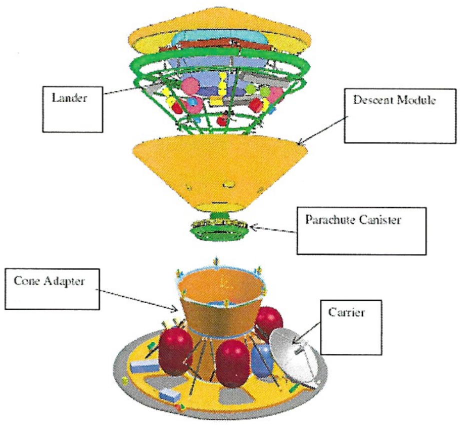

Fig. 18:Spacecraft design

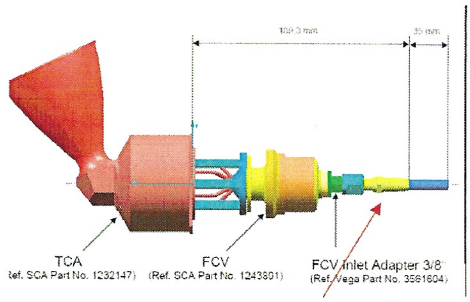

Figure 19 Connection of thruster to tubing system

The complete installation of the propulsion subsystem is shown in Fig. 20

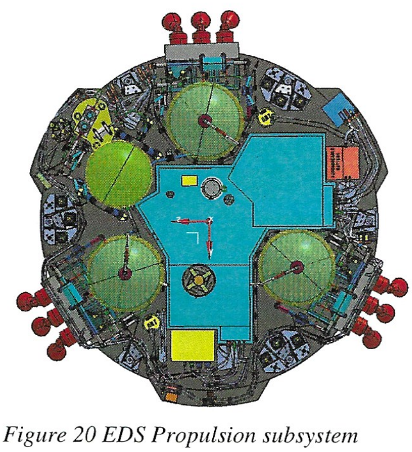

Figure 20 EDS Propulsion subsystem

The carrier concept was originally based on a dual mode-propulsion system using N2H4 as propellant for the AOCS Monopropellant thruster and for the injection maneuver into the Mars orbit an engine operation with N2H4 /NTO. However, such propulsion components are not available in Europe. OHB, responsible for propulsion, thermal and structure of the carrier, traded the use of a standard bi-propellant system (e.g. standard Telecom propulsion subsystem). The selected carrier structure with a central tube as shown in Fig. 8 is very similar to the standard structure of Telecom buses. Therefore a standard UPS was selected with wide European heritage and the advantage of lower prices with the use of mainly European components.

8.3 MTE and Antiope –Throttleable engine investigation

Within the overall ESA exploration framework throttling descent technology has been identified as an enabling technology for future (larger) lunar lander missions. As such, development activities for larger throttelable engines are included in the ESA Exploration (service domain 3) technology roadmap and also within the Technologies for exploration roadmap (currently under definition).

One key requirement for future lunar missions is to reduce the propulsion system mass fraction w.r.t current concepts. The MTE contributes significantly to such a reduction by doubling the engine thrust to mass ratio, while providing much of the necessary control function at vehicle level.

Agency near term goals for the development of throttling technology encompass not only this study but also the parallel ANTIOPE study, co-funded with Astrium under the ESA GSTP program. In this study, preliminary investigations have been initiated into the basics of pintle injector design and associated performance characterization. Test results from the ANTIOPE activity are currently under analysis and will be used, in conjunction with the outputs of the MTE study, to guide further design iterations of both the pintle and associated chamber geometry.

The primary aim of the ANTIOPE activity is to provide the necessary design database for the pintle injector technology at the entry to the development program outlined in the MTE study (ref).

Fig. 21 shows a cold-flow test and figure 14 shows the cut-drawing of the engine design. Thrust level is 8KN

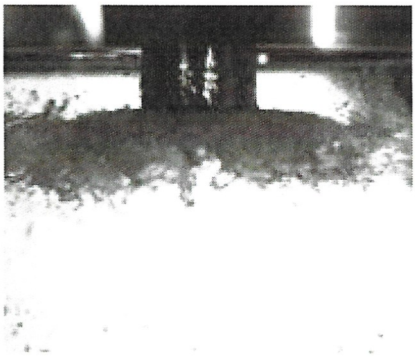

Figure 21: Injector cold flow test of the GSTP technology demonstrator

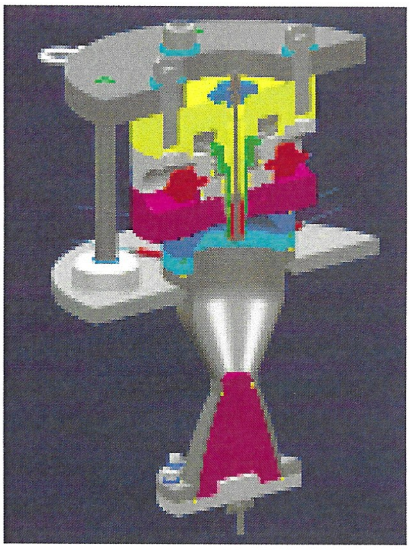

Figure 22 GSTP Technology demonstator

9. STORABLE PROPULSION NEEDS

Launcher Propulsion

For launcher propulsion, the need of a high performance engine in the thrust class of 3 - 8 kN is identified. This engine should be capable to be re-ignitable, with a long duration single burn requirement of approx. 20 minutes. Such engine can be used for kick-stages in order to come to more flexible launch vehicle missions as well as for the MPCV in the extend crew version to separate the MPCV from Launch vehicle when a crew is on board.

In addition, the Aestus II engine with high performance has a good potential to be applied for VEGA performance improvement and/or for Ariane 5 dedicated science or robotic missions.

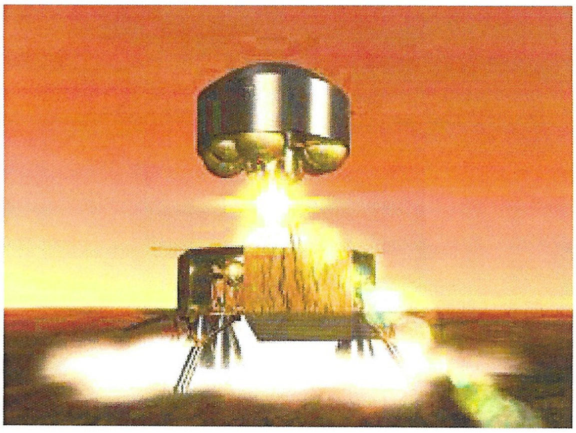

Figure 17: ESA's lander & ascent capsule, with different propulsion systems.

Around 2025, ESA plans to bring samples back from Mars to Earth. This Mars-Sample-Return mission requires (beside the Mars orbiter and the descent vehicle) also an ascent vehicle to rendezvous with the orbiter and a flight mission back to Earth. For such a mission a 8 - 12 kN engine is needed for descent. For ascent the engine shall operate in steady state at the maximum performance. These diverging requirements could be met by different engines (variable thrust for descent, high performance for ascent) as illustrated in the artist view of the ascent of the MSR mission, see Fig. 17.

For Mars orbit insertion of the orbiter, ESA identified the need of a propulsion module with 1 up to 1.5 kN of thrust.

Appraisal of engines for Exploration

For the todays planned mission Lunar Lander, Exomars 2016, MPCV and MSR the appraisal regarding the most time and funding consuming component were performed.

1. For the lunar lander mission only qualification of the EAM and the 200 N thrusterare needed. ➔Adaptation effort, no new development.
2. ExoMars carrier (and later on the Orbiter) to use a standard bi-propellant propulsion system (in use for telecom missions) based on a 2 -tank version with the 400 N LAE.

   ➔ Adaptation effort, no new development.
3. For the MSR which calls for an orbit insertion thrust of 1 - 1.5 kN Astrium proposes to use 3 clustered EAM engines. Investigation regarding thermal interferences of the engines to be investigated.
   ➔ Adaptation effort, no new development.

   However, ESA initiated a development of a 1-1.5 kN engine in the MREP program.

4. For the MSR descent & ascent propulsion system it is proposed to initiate a trade –off study regarding the use of the engine under development within FLPP programe: thrust level up to 12 kN or a throttlabe Engine 8- 2.5 kN including steady state operation

   ➔ Development of one engine instead of two new ones.

For upper stage engines, the continuation the FLPP Storable pre-development program is needed: The technology program will be finalized in 2014 and shall be continued with a development / qualification program for product availability beyond 2016.

10. SUMMARY AND RECOMMENDATIONS

The proposed ESA missions up to 2025 were analyzed regarding their engine and thruster needs. The main results and recommendations are:

1. EAM is corner stone product in the 500 N class, to be delta-qualified for commercial application, MPCV and the Lunar Lander. For Lunar Lander the effect of interferences with the 5 clustered Engines to be investigated. From analytical point of view this seems to be not critical. The engine is also suitable to be used in a clustered version to cover 1 - 1.5 kN orbit insertion requirements. It is recommended to identify the requirements for an extension of the planned qualification.
2. The pulse mode operation of the 200 N thruster shows excellent results in accordance to the Lunar Lander mission requierements. Additional Pulse mode operation with the 22 N thruster will mitigate the technical risk for the Lunar Lander program.
3. For MPCV (crew- version) a 30 - 40 kN engine could be based on Aestus heritage or could be fulfilled by clustering of 8 kN engines; the development shall be started eight years in advance to the planned mission.
4. Key technology for throttleable engines is the pintle-injector technology. Today it is planned that the technology shall be built up within Astrium R&D program within a GSTP support of 50% up to the end 2013. The development of a full scale engine shall be considered by ESA with a breadboard demonstration from 2014 onwards.

11. List of Abbreviations

Antiope

ATV	Automated Transfer Vehicle
ARV	Advanced Return Vehicle
AOCS	Attitude Orbit Control System
CHT	Chemical Hydrazine Thruster
CDR	Critical Design Review
EAM	European Apogee Motor - Astrium Brand name
EDS	Entry Decent System
ε	Ratio between nozzle exit / throat area
FLPP	Future Launcher Preparation Programme
GTO	Geostationary Transfer Orbit
GEO	Geostationary Earth Orbit
Homer	Hover Maneuver…
HSF	Human Space Flight
ISS	International Space Station
Isp	Specific impulse
LAE	Liquid Apogee Engine
MMH	Monomethyl Hydrazine N2H3(CH3)
MSR	Mars Sample Return (planned ESA Mission)
MPCV	Multi-Purpose-Cargo (Crew) vehicle
NTO	Nitrogen Tetroxide N2O4
RCT	Reaction Control Thruster
SCA	System Control Attitude (Launcher Roll-Control System)
SRE	Science Robotic Exploration
TAS-I	ThalesAleniaSpace Italy
TRL	Technical readiness level
UPS	Unified Propulsion System

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