Propulsion Technologies - Present Status and Future Needs for Exploration

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Abstract

Propulsion is an indispensable element for all future space challenges. European concentration in the last 30 years in this sector was focused mainly on launcher and satellite propulsion applications. Now, Europe's future view for exploration on the Moon and Mars missions calls for the development of new propulsion technologies. This paper gives an overview of the currently available systems and component technologies. It shows by segmentation, which technologies could be adapted and which have to be developed for robotic missions in a first step and for human space flight in a second step. In addition, a screening of the technologies and a roadmap of the technologies to be developed is proposed to fulfil Europe's ambitious plans for space exploration.

1. INTRODUCTION

All ambitious missions in exploration will only be possible if adequate propulsion systems for transportation, descent and ascent are available. Within the last 2 decades, technologies and products were developed to fulfil the needs, mainly for the transportation of satellites to GTO and LEO on launchers and spacecraft propulsion, for Earth applications (weather, telecom, broadcast). Updates of these systems were used for specific scientific missions like Ulysses, Hipparcos, Mars Express and Rosetta.

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:

- Descent manoeuvres with soft and precise landing
- Ascent and rendezvous in orbit with precision docking
- 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 and the amount of available hardware. 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

Astrium ST has initiated and performed an internal investigation into exploration propulsion, the results of which are discussed in this paper. 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 European national organisations
- Short and medium term focus on unmanned missions. Long term focus (2025 and beyond) on manned missions - first to the Moon, then to Mars

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. LIQUID PROPULSION SYSTEMS HERITAGE IN EUROPE

Europe has a long and extensive heritage in Propulsion system

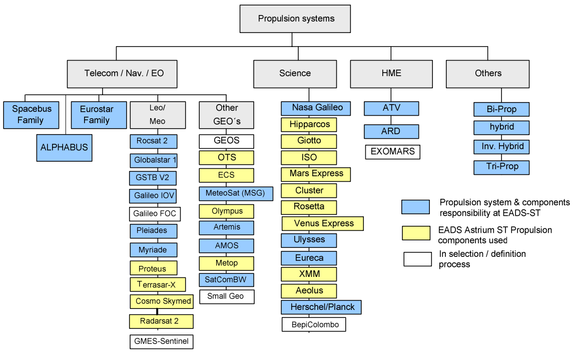

Fig.1: Liquid propulsion system heritage in Europe

The European propulsion industry has gathered extensive experience in propulsion systems for telecommunication programmes. Since the mid 1980's approximately 120 systems have been built and delivered to system primes.

Unique systems were designed, developed and integrated for science missions. 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.

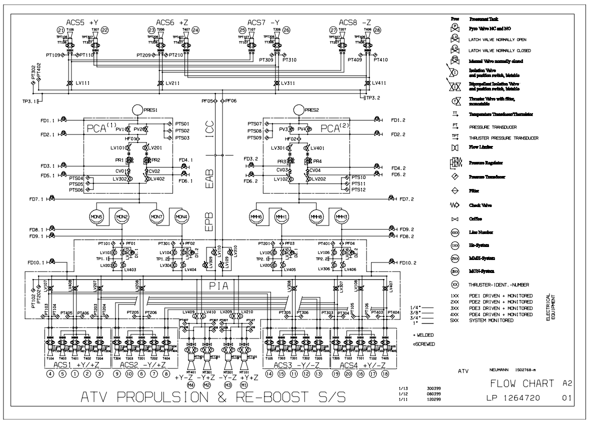

Fig. 2: The ATV propulsion system

The system comprises 28 x 220 N pulse mode thrusters and 4 x 400 N 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.

3. AVAILABLE RE-ENTRY PROPULSION TECHNOLOGY

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

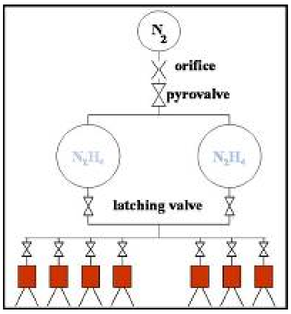

Fig. 3: ARD propulsion system

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

The thrust level was throttled by the tank pressure, since the system was used in blow-down mode. The following table shows the qualification performance data:

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

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

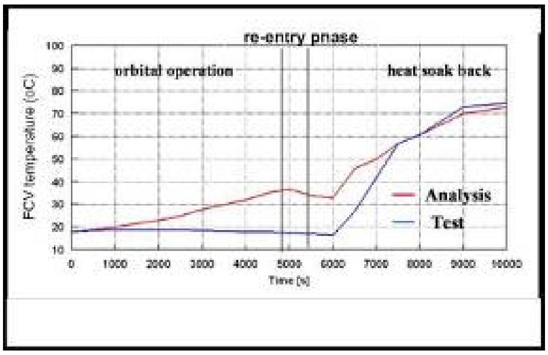

Diagram 1: Flow control valve temperature versus mission time

The following figure illustrates the complete ARD mission, which was performed successfully in 1996.

Fig. 4: ARD mission [10]

4. PLANNED EXOMARS MISSION

In 2013, ESA plans to launch the EXOMARS Mission[1,2,], with its carrier, the Decent Module (DM) together with the Entry Decent and Landing System (EDLS) which will be separated during a "fly-by" manoeuvre of the carrier during an hyperbolic orbit. The DM shall be landed softly in order not to damage the rover for its trip on the Mars surface.

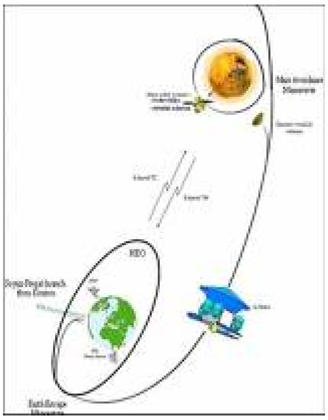

Fig. 5: Mission profile

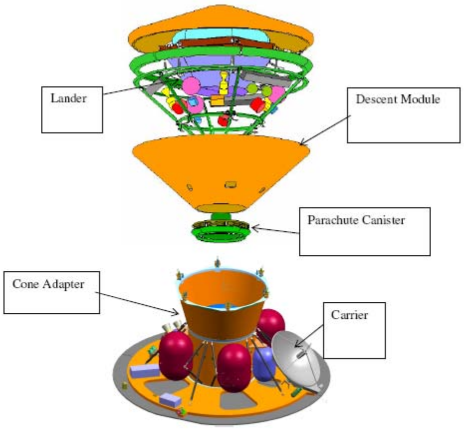

Fig. 6: Spacecraft design

The lessons learnt from the Mars Express mission, with its Beagle Lander, indicated that a landing mission without an active propulsion system has a high degree of risk in losing the mission. This seems to be the case for the Beagle descent mission. Based on this assumption, ESA decided to investigate two landing philosophies, thus:

1. Solid rocket motor braking manoeuvre, supported by a liquid propulsion system with capsuled airbag solution
2. Soft landing with liquid propulsion and a lower floor airbag damping system.

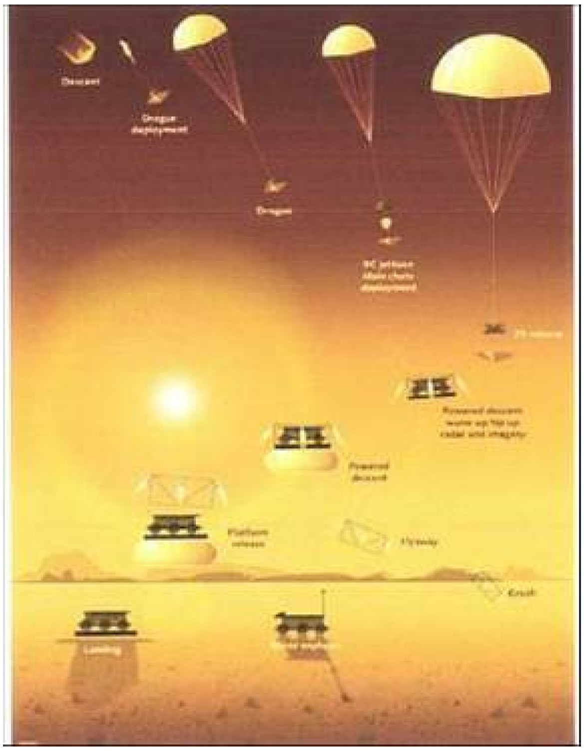

Fig. 7: Baseline EXOMARS landing mission [10]

The scenario actually investigated was based on the following steps:

1. Entry into Mars atmosphere with heat shield
2. Parachute deployment
3. Separation of parachute
4. Liquid propulsion braking and attitude control manoeuvre (option: solid rockets for braking and hydrazine thrusters for attitude control)
5. Airbag deployment
6. Final landing position definition
7. Separation of propulsion module and drop down with the airbag as damping system
8. Coordinated fly away of the propulsion module, far away from the Rover landing position

The investigation of a liquid propulsion system for a soft and precise landing was contracted by Thales Alenia Italy to two B1 studies, one performed by Thales-Alenia (France) and one by Astrium ST (Germany).

The general conditions for these investigations were:

1. Launch in 2013
2. Respect for planetary protection
3. Throttleable engine(s) instead of pure pulse-mode firing and "shock" generation for the payload (Rover and other experiments).

The first important point for EXOMARS is that currently the launch is scheduled for 2013. Up to this point of time, any engine development has to be finalised no later than 2010 - in order to have sufficient margins for propulsion system integration and tests. Therefore the focus was set on available or CDR level available hardware. This is the case for both the proposed hydrazine engines (Astrium-ST 2500 N Engine and a 3500 N US product).

Secondly: Planetary protection is an important aspect linked with the "export" of any biological particles to a target planet with atmosphere. Respecting this requirement, all currently performed missions, especially the US missions to Mars, were and will be performed with the propellant hydrazine.

To fulfil the EXOMARS landing mission, throttleable engines or engines operated in pulse and off-modulation mode are required. By clustering, the necessary total thrust level for braking, attitude and roll control can be achieved. European hydrazine engines, their development funded by ESA and DLR, are available. These include the 2500 N thruster, developed and tested in a quasi-flight type configuration and the highly qualified and flight proven Ariane 5 SCA 400 N thruster. The 2500 N thruster could easily be equipped with a throttle valve, while the 400 N thruster has been qualified for steady state, pulse mode and off-modulation firing.

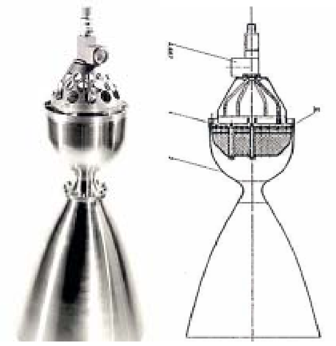

Fig. 8. The N2H4 -2500 N hydrazine engine

Fig. 9: Piece parts of the 2500 N engine

However, the Astrium ST results have a clear preference for the 2500 N throttleable engine, which has been developed with German national funding and could now be used for EXOMARS. The needed thrust range of approximately 12 kN will be achieved by using 6 of these engines. In this context also, the procurement of a US Engine, as an alternative soft landing liquid propulsion solution, is under discussion. The disadvantage of a pure procurement solution is that no European technology within this field will be developed and be available for future missions.

As an option to the soft landing with a liquid propulsion approach, a landing with solid rocket motors for braking and 400 N SCA thrusters for attitude control and precise positioning is proposed.

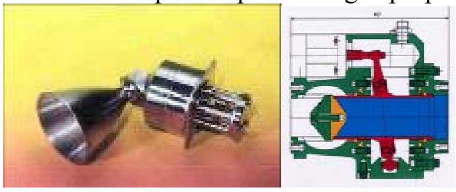

Fig 10: The 400 N engine, control valve (examples) [3]

5. STATUS OF PROPULSION TECHNOLOGIES

In addition to the investigation of a liquid propulsion system for soft and precise landing for the EXOMARS project, a screening of available technology levels together with the identification of the type of propulsion technology to be developed within the next years was investigated by Astrium ST. Here, it is mandatory to consider both the European long term scenario for science missions as well the ambitious plans at national as well as international level (ESA, EU).

For the EXOMARS mission, only an adaptation of existing hardware is compliant with the schedule. Also, the required Δv of 50 m/s for the soft landing should not call for the creation of a new technologies or hardware.

For all robotic missions required for the investigation of any planet surface, propulsion is needed for the following items:

1. **Carrier**
   Transfer to and orbit insertion around target planet and/or fly-by
2. **Module (payload)** to be deployed for descent to the target planet
3. **Ascent** to return samples to earth

For the carrier propulsion system, a broad heritage is available from telecommunication satellite bus platforms. These system technologies would only require slight adaptation for the required propulsive needs. Here, the main advantage would be the use of components having a long demonstrated flight heritage. This philosophy has proven to work in the past and where systems were adapted for e.g. EXOMARS and Venus Express. Consequently, the carrier propulsion module would be based on a bi-propellant propulsion system with orbit and attitude control thrusters and a kick engine for the orbital insertion toward the target planet. The insertion into the required spherical or hyperbolic orbit could already be performed by the launch vehicle without the need for a kick engine.

For the descent of the payload toward the target planet, a throttleable engine, as well as its propulsion system, would need to be developed. Currently, only a few components are available from existing flight proven programmes. The main development effort would be applied to the high flow rate components such as the pressure regulator, pyro valves, fill and drain valves, latch-valves, propellant tank inlet and outlet design.

For missions with ascent such as Mars Sample Return, the weight factor becomes more and more important. Currently only ascent with bi-propellants seems to be feasible for both, planets~~,~~ with or without atmosphere.

One major assumption within the Astrium ST investigation is to use, as much as possible, commonalities between the different carrier, descent and ascent applications. This will have an impact on both the mass for a dedicated mission vehicle (and the needed launch capability) as well as the level of effort required for the development and procurement activities for the planned mission.

Fig. 10 shows the performed screening of the different propulsion technologies and their development potential.

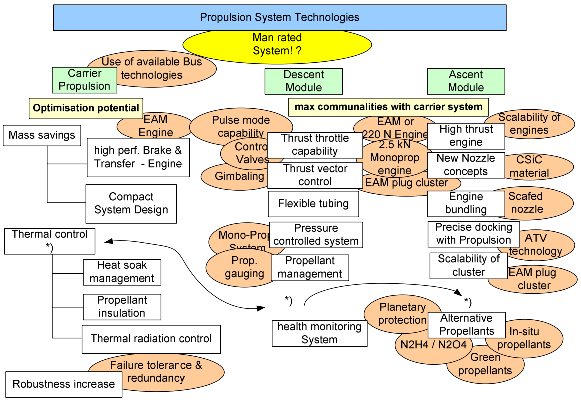

Fig. 11: Technology screening

a) **Carrier propulsion technologies** have the main objectives of inserting the "payload" into its final orbit around the target planet, or injecting the payload into a fly-by manoeuvre. The currently planned missions have weight limited payloads ranging from several kilograms, to several tonnes. The technology and heritage derived from the telecom bus platforms have proven applications for both the use, and gathering of explorative propulsion technologies. For example, propulsion systems derived from telecommunication platforms have already been used on the German propulsion system used on NASA´s scientific Galileo mission. Similarly, with Mars Express and Venus Express, both spacecraft operate in their target planet orbit. In this respect, the current Technology Readiness Level (TRL) is close to 9. The areas required for improvement are known and are part of the developments. The main benefit for industry is use of the robotic mission heritage for improvements to the bus platforms of the telecom satellites.

In the first conclusion, the currently available bus technologies from probes and satellites are adaptable for all planned robotic missions used for sending a payload of several tonnes to the target planet.

b) **Descent technology** has two main thrust requirements: 1) High thrust engines, and 2) Lower thrust throttleable and / or pulse mode engines. High thrust engines are required for high velocity retro-burns used during the initial descent-braking toward target bodies without atmosphere, such as the Moon. Lower thrust throttleable engines are required for the final precision approach and soft landing. The two different thrust level requirements may vary by a factor of TBD. In the case of EXOMARS, precision landing requires a total thrust of 10 kN. The thrust level of all engines, and where applicable the pulse mode (min. impulse bit) and throttling capability will need to be adaptable according to the mass to be landed. In the case of descent braking propulsion, a number of technologies already exists that will accommodate the varying thrust requirements with a TRL of up to 5. Here, development needs to be initiated at both component and systems level, e.g. the ability of high flow rate components, such as latch valves, to have adequate switching time. At systems level, e.g. the ability to control pogo (water hammer) effects.

c) Ascent technology calls for a high thrust level, either as a single or clustered engine pack. However, the thrust range commences with a thrust level of > 10 kN. Currently, in Europe only the Aestus engine is available.

The different propulsion needs are given in the following table:

Main Engine Requirements	Carrier Module	Descent Module	Ascent Module	Remark
specific impulse	X		X	Highest possible for Carrier and Ascent Module
long duration firing capability			X	
firing under atmospheric conditions		X	X	
thrust variation				
pulse mode & off-modulation firing capability		X		
thrust control by throttle valve		X		
fast response		X		
constant thrust operation	X		X	
thrust range	400-800 N	> 12 kN	> 10 kN	depending on payload mass
separate attitude & roll control system	X		X	
planetary protection requirement		X	X	

Table 1 Comparison of different propulsion needs

In the following, only some examples of available technologies will be presented and discussed. The main objective is to show the wide scatter of available technologies. However, TRL ranges from 2 to 4 and up to a maximum of 5. To make existing technologies ready for future robotic missions, the most promising candidates are pre-selected and investigated, within say, the Technology Readiness

Programme. Here, the investigations are advanced to a level in readiness for the final dedicated mission development and qualification requirements.

1) System aspects
   Within non-space programmes, there are examples of simple, very reliable systems in use. This is especially the case, if after a long storage period (in some cases years) the system will be activated and placed in operational mode. Within the following example, the pressurisation of the propellant tanks is achieved by hydrazine gas produced by a gas generator. In addition some of the gas could be used for attitude control. In order to prevent hydrazine gas mixing with the oxidiser or fuel the pressurant gas will be isolated from the propellants using piston type propellant tanks. This technology has several advantages that can be used for ascent applications.

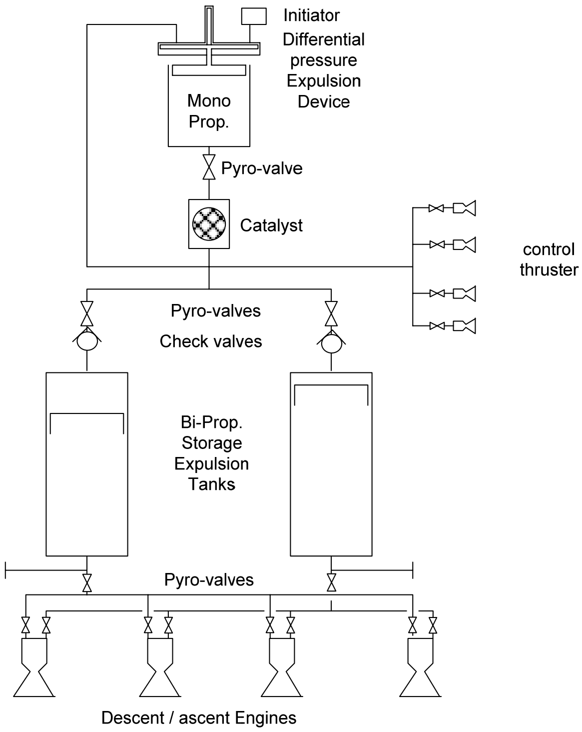

Fig. 12: Propulsion system [4]

2) The use of a plug engine cluster is an interesting technology prospect [9], especially with the current technology level of existing materials. With the availability of CSiC materials, the combustion temperature level could be extended to about 2000 K.

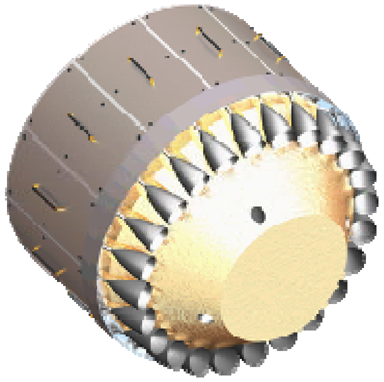

Fig. 13: Plug cluster based on Apogee engines

   With such a concept, throttle ability can be achieved in a step mode function by selectively operating clusters of diametrically opposite engines (4 or 8, or 16, etc). ARCS manoeuvres can also be realised with this system, depending on the total diameter. The overlapping effect of the engine main jet stream has already been performed on linear plug and thermal / aero-dynamic models. The theoretical models were subsequently converted to hardware models, which in turn, were adjusted and refined by testing.

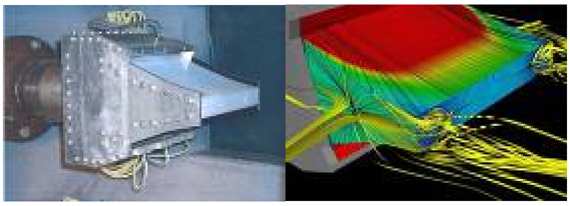

Fig. 14: Linear plug testing and modelling

At systems level, a structural mass saving can be achieved by reverting to a well proven classical propellant tank configuration with integral engine attachment interface and the use of modern lower-weight materials. Here, the propellant tank comprises a cylindrical section with an upper and lower dome. An internal dividing bulkhead is used to create two separate chambers for the oxidiser and fuel. The engine will be mounted directly to the lower tank dome, which is designed as a thrust structure. The cylindrical tank section would also be designed as a thrust structure, thereby removing the need for a separate outer cylindrical section.

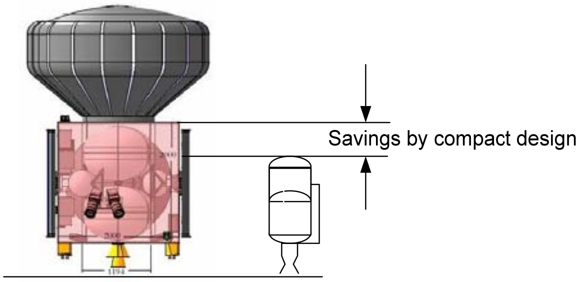

Fig. 15: Structure savings by compact design

3) New Engine / nozzle concepts
At Astrium ST, higher performing engine concepts have been realised through the use of CSiC materials. With this material, the synergetic benefits include a one-piece nozzle and combustion chamber, higher operating temperatures, with an expected Isp of 325 - 327 s using the bipropellant combination MMH / N2O4, fewer components and reduced mass.

Fig 16: Sea level testing of ceramic engine

Gimballed engines with a high epsilon rate of the nozzle extension have the disadvantage of limited angular acceleration. With a single plug engine, the nozzle length can be significantly reduced, leading to a corresponding reduction in the length, and mass, of the landing legs of the vehicle. In combination with a pintle injector, mechanically coupled with the plug, the chamber pressure could be constant during thrust variation, leading to advantages in combustion efficiency.

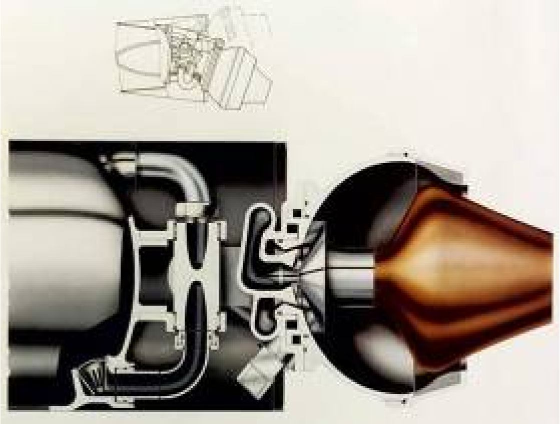

Fig. 17: Single plug engine [4]

To demonstrate the technical concept, several seconds of hot fire testing has already been performed. With the current availability of CSiC technology, a plug could be realised to withstand long-term firing durations.

During the last years, several engines with CSiC nozzles have been tested. In addition to the advantages previously mentioned, the tests have also shown an increase in robustness, especially at the nozzle throat. Tests with LOX / LH2 have also shown that CSiC is capable of withstanding very high temperatures [5].

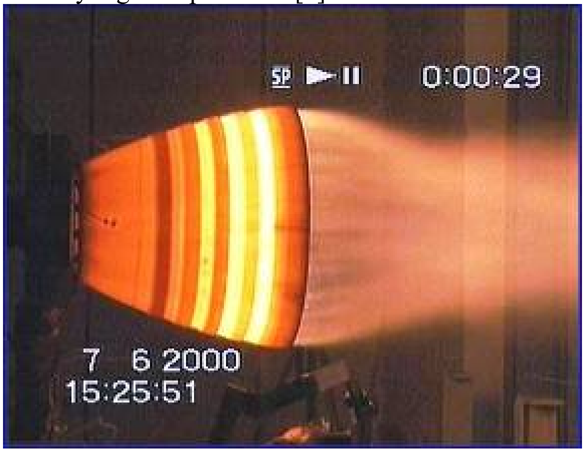

Fig. 17. Vulcain subscale nozzle under test conditions

5) It has been demonstrated that a cluster of engines can be adapted to create a single exhaust stream capable of thrust vector steering. In the example that follows, 4 such engines, with rotatable segmented nozzles, were clustered to achieve thrust vector change.

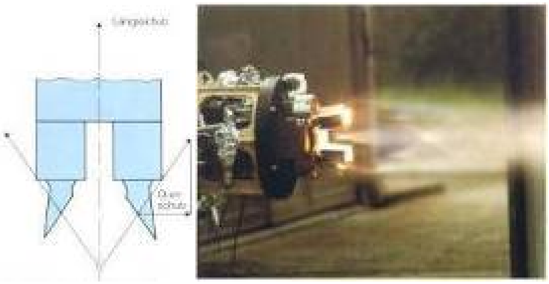

Fig. 18: Clustered engines under test firing [4]

6. PROPULSION TECHNOLOGIES AND LANDER CONCEPT

ESA's long term planning for science and exploration missions is now organised and coordinated by the SFE Directorate. These missions will gather information through orbital observation and direct contact by robotic operations. Earth's Moon is an ideal body that is conveniently placed to verify the propulsion technologies necessary for space exploration and robotic missions. The initial robotic missions to the Moon will have tremendous scope for evolution associated with lunar exploitation, infrastructure development, habitation, human space flight and as a staging post for missions further afield.

In the absence of an atmosphere, a lunar landing demands a propulsive braking which is more demanding on the propulsion system than a landing on Mars. For a lunar landing, the braking Δv is about 2000 m/s, compared to about 50 m/s for a Mars landing. Fulfilling both of these braking requirements with a common propulsion concept would currently appear difficult to manage.

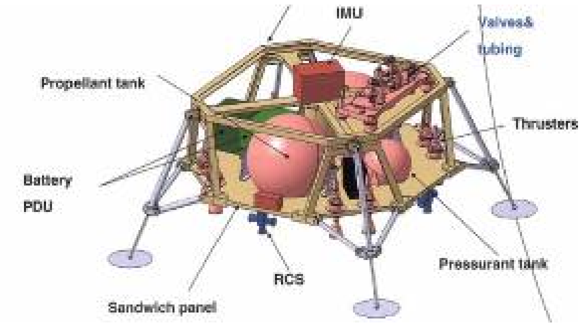

Fig. 19: Lander concept

Considering the available propulsion technologies, a future Moon / Mars Lander will have a different design. For example, by using plug cluster propulsion, the landing leg could be drastically shortened. The current length of landing legs is needed in order to guarantee a minimum space between the main engine and the ground, (as can be seen, for example, from the Moon Lander used on Apollo 14.

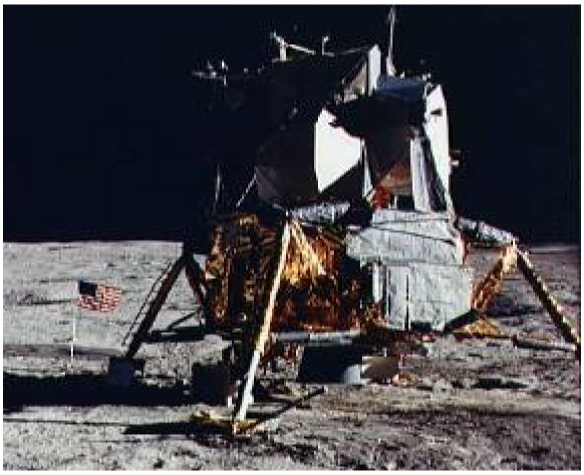

Fig. 20: NASA - Apollo 14 Lander [11]

7. SUMMARY AND RECOMMENDATIONS

The presented paper shows the portfolio of very interesting technologies for a lot of different applications at different TRL levels. Now, a clear identification is needed which technologies have to be selected for product /system developments. Europe has to be prepared for the different planned ESA missions to Moon , Mars and beyond. The summary of the highlights are:

- Technologies / systems for the carrier shall be based on mature spacecraft propulsion system technologies.
- To safeguard and choose the best solution for the planned missions, ESA shall initiate an European screening of all available technologies, systems and components, soon as preparation for the technology to product roadmap.
- Ascent & orbit docking with propulsion technologies shall be first investigated within trade-off system studies. This shall be initiated by ESA soon to choose the most reliable and efficient concept.
- The technology to product roadmap shall be created for all sensible components of the propulsion system. This shall cover throttable engine, compact tank concepts, pressure regulator, pyro valves, latch valves, etc and their potential to be used as a further application within man-rated systems also in redundancy to cover also unexpected emergency cases.
- Alternative and challenging advanced technologies (e.g. cryogenic propellants like methane /Ox , in-situ propellants like higher-silane) to be investigated concerning the potential of short mid- and long term availability on component and system level.

One main focus to be set on the development of a throttable bi- propellant (NTO/MMH) or dual mode engine (NTO/N2H4). Such a demonstrator programme has to be decided during the next ministerial conference. Such engine could be used for descent and ascent applications and will demonstrate Europe's willingness to play a major rule within exploration as partner for other countries as well as independently.

8. REFERENCES

[1] Council Working Group for the preparation of the Council meeting at ministerial level
The Director General's Proposal: Context and Objectives, ESA document, April 2008

[2] ELEMENTS OF THE DRAFT ESA LONG-TERM PLAN 2008-2017; ESA document, December 2007

[3] EADS-Astrium space transportation Web page www.space-propulsion.com

[4] Internal Report on propulsion technologies for non space application; reporting period 1977 - 1998

[5] G. Hagemann, J. Alting, D. Preclik; Scalability for Rocket Nozzle Flows Based on Subscale and Full-Scale Testing.

[6] The vision of Space exploration he vision of Space exploration; Jet Propulsion Laboratory http://www.nasa.gov/mission_pages/exploration/main/index.html

[7] Jesco v. Puttkamer, Jahrtausendprojekt Mars 1996, ISBN 3-7844-2571-2

[8] 50 years of space, a global Perspective; Astronautical Society of India (ASI) 2007 ISBN 13-978-81-7371-600-3

[9] D. Huzel, D. Huang: Modern Engineering for Design of Liquid-Propellant Rocket Engines, 1992 ISBN 1-56347-013-6

[10] ESA WEB page www.esa.int

11] The Appollo Program http://www.nasm.si.edu/collections/imagery/apollo/AS14/images/AS14_LSMnt.jpg