114-VS-5

Session Mars Vehicle Systems

AIAA-2009-5266

Status and Outlook of Descent and Ascent Propulsion Technologies for Moon and Mars Missions

Hartwig Ellerbrock,
Dr. Gerald Hagemann
Markus Peukert
Hans Dieter Schmitz
Mark Kinnersley

EADS Astrium Space Transportation,
Munich / Lampoldshausen/ Bremen, Germany

45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 2 - 5 Aug 2009 Colorado Convention Center Denver, CO

114-VS-5
AIAA-2009-5266

Status and Outlook of Descent and Ascent Propulsion Technologies for Moon and Mars Missions

Hartwig Ellerbrock
EADS Astrium Space Transportation,
Propulsion & Equipment,
81663 Munich Germany
E-mail: hartwig.ellerbrock@astrium.eads.net

Gerald Hagemann, PhD
EADS Astrium Space Transportation,
Propulsion & Equipment;
81663 Munich Germany
E-mail: gerald.hagemann@astrium.eads.net

Markus Peukert
EADS Astrium Space Transportation,
Propulsion & Equipment
74215 Moeckmuehl, PO-box 1119, Germany
E-mail: markus.peukert@astrium.eads.net

Hans-Dieter Schmitz
Senior Propulsion Consultant
79312 Emmendingen, Bachstraße 25
E-mail: HDSchmitz@t-online.de

Mark Kinnersley, PhD
EADS Astrium Space Transportation,
Orbital Systems;
28361 Bremen Germany
E-mail: mark kinnersley@astrium.eads.net

Abstract

The paper gives an overview of the European current status of propulsion technologies on system as well as on component level. The today's available propulsion technologies are put into comparison to the needs of propulsion systems / components for space exploration missions.
A more detailed focus is set on the propulsion technologies proposed by EADS Astrium for final soft and precise landing of ExoMars with an outlook of these technologies to be used for further 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, the descent- and for some missions also the ascent propulsion are available. Within the last two decades, technologies and products were 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 Mission GALILEO, Mars Express, Rosetta and for re-entry demonstration missions like ARD (atmospheric re-entry- demonstrator.

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).
- Descent manoeuvres for non atmospheric goal planets (break-manoeuvre) e.g. Moon.
- A soft and precise landing on the surface.
- 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. 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 launcher, 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 & Mars mission under investigation at ESA & DLR (next-Lunar-Lander, Lunar Cargo-Lander, ExoMars, and Mars sample return). 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 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. LIQUID PROPULSION SYSTEMS HERITAGE IN EUROPE

EADS-Astrium ST is one of ESA`s reliable and dependable propulsion partner and has demonstrated with components and subsystems for the missions its competence in propulsion.

The European propulsion industry has gathered extensive experience in propulsion systems for tele-communication programmes. Since the mid 1980's approximately 140 systems have been built and delivered to commercial primes and Agencies.

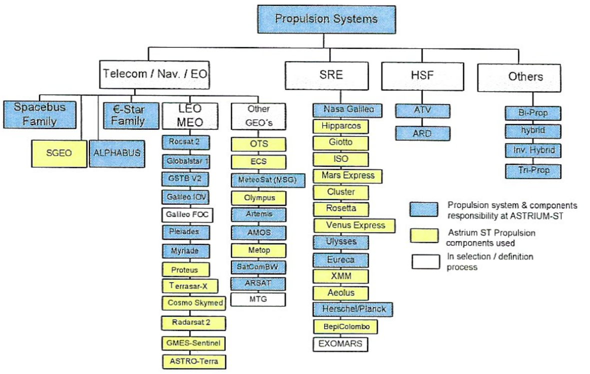

Figure 1:Liquid propulsion system heritage in Europe.

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.

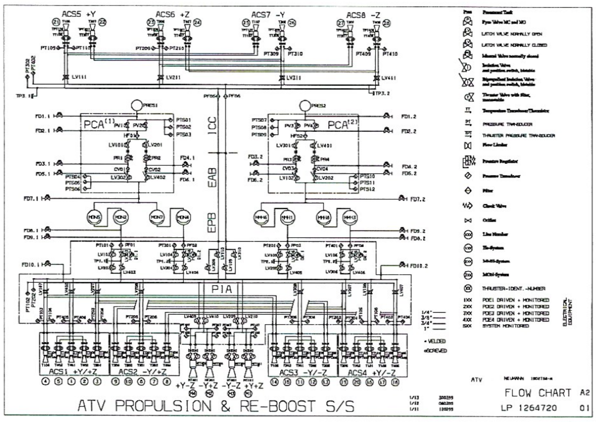

Figure 2: The ATV propulsion system.

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.

3. 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.

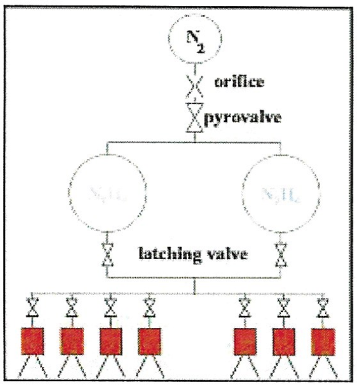

Figure 3: ARD propulsion system.

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.

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.

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

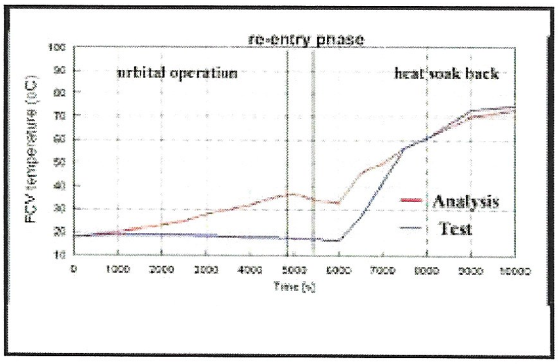

Figure 4: Flow control valve temperature versus mission time.

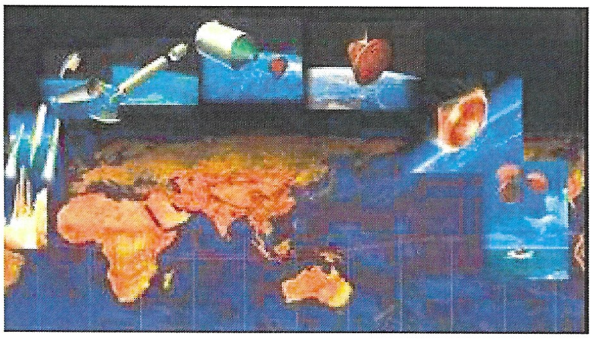

Figure **5:** ARD mission [10].

4. ENVISAGED MISSIONS

4.1 Mars Mission:

In 2015/16, ESA plans to launch the ExoMars mission [1,2], with a carrier~~,~~ and a Decent Module (DM). The Decent Module includes the Entry, Decent and Landing System (EDLS). After separation from the orbiter the DM shall be landed on the surface of Mars.

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 loosing the mission.

An investigation of a liquid propulsion system for a potential Mars mission with soft and precise landing capability shall respect the following elements:

1. Launch within the next 5 years.
2. Respecting the planetary protection requirements and prevent the use of Hydrocarbons.
3. Considering throttleable engines instead of pure pulse-mode firing, resulting in "shock" generation for the payload (Rover and other experiments).

The first important point is the schedule requirement. A launch within 5 years requires that the propulsion system including the engine development has to be finalised not later within the next 3 years - in order to have sufficient margins for propulsion system integration and tests. Therefore the focus has to be set on available or CDR level available hardware. This requirement is fulfilled by monopropellant engines and thrusters of Astrium ST that would be needed (2500 N engine, 400 N engine and 20 N thruster).

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.

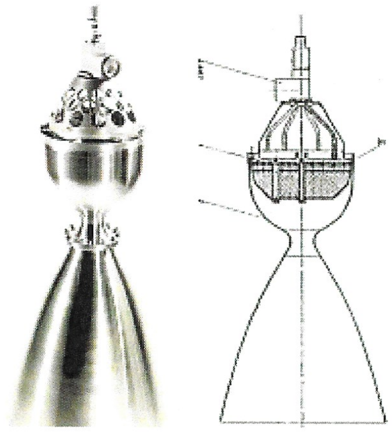

Figure 6: The N2H4 -2500 N hydrazine engine.

To fulfil a Mars landing mission, throttleable engines or thrusters shall operate in pulse- and off-modulation mode conditions. 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 fast acting flow control-valve, while the 400 N engine has been qualified for steady state, pulse mode and off-modulation firing.

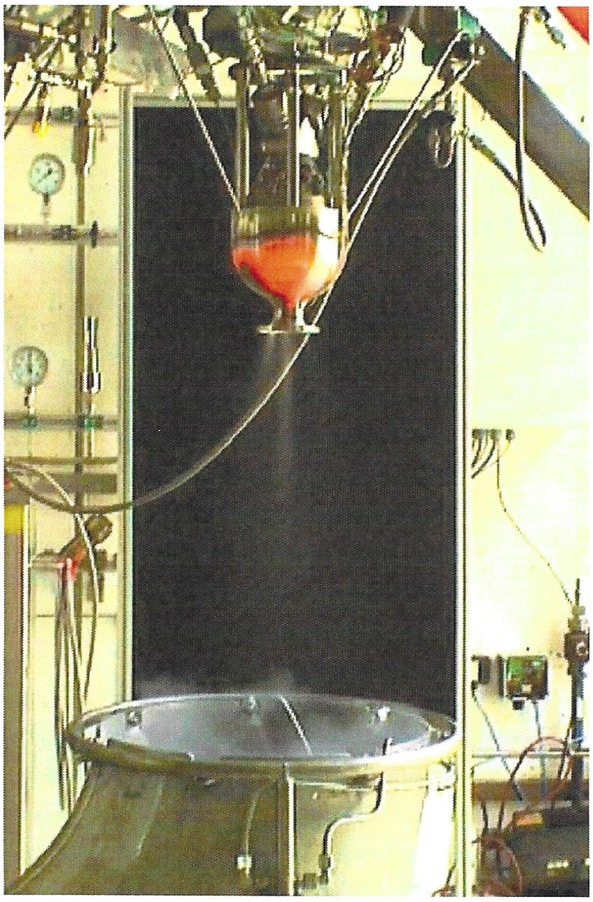

Figure 7: 2500 N engine under sea level test (w/o nozzle extension).

In order to reduce engine development and qualification risk Astrium ST has performed hot firing tests with the 2500 N engine in 2008 at high, nominal and very low impulse bits. The results are given in Fig.8.

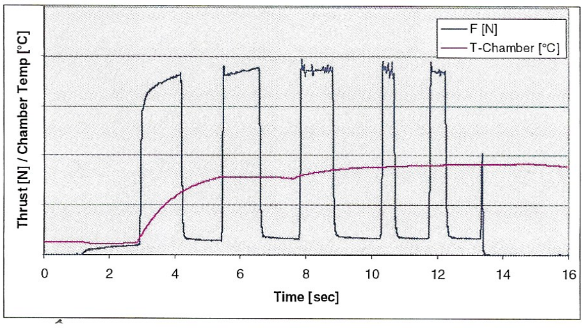

Figure 8: Results of the 2500 N hot firing test.

ESA has a clear preference to use European hardware for their missions when available and the 2500 N throttleable engine, which has been developed with

German national funding and could now be considered as an European product for any potential Mars mission. A typical thrust need of approximately 3.5 - 4 kN could be achieved by using one 2500 N engine and some 400 N engines for roll-control thrusters or 9 x 400 N SCA thrusters. A trade-off study is investigating the best solution of the mixed system

As an option to the soft landing with a pure liquid propulsion system, a landing with solid rocket motors for braking and 400 N SCA thrusters for attitude control and precise positioning could also be considered and is also part of the trade-off investigation

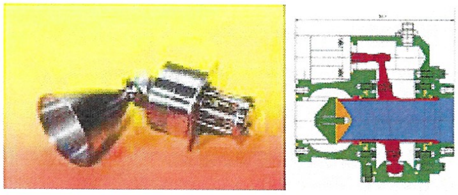

Figure 9: The 400 N N2H4 engine, and a control valve (examples) [3].

4.2 Missions to the Moon

Several Lunar missions are currently under investigation all over the world. Landing on the Moon requires due to the absence of the atmosphere a significantly higher ΔV than the soft landing on Mars surface and will be above 2000 m/s, depending on mass and mission compared to a soft landing demand on Mars which is around 50m/s.

All "break-Manoeuvres" could be performed with a bi-propellant system using MMH/NTO as propellants. This is a high advantage, because this allows using as much as possible thrusters/Engines with flight heritage and space qualified components. One option is also to use for the descent the same types of engines as in use for the ATV automated transfer vehicle: 220 N and four 500 N thrusters and engines as well as the components. Unlike the ATV, however, the landing module cannot be brought to a standstill in space, so it needs to control and slow down its approach during the entire descent. This could be done by pulsed engines that work asynchronously, i.e. that can be switched on and off at alternating times.

Both engine classes are under Astrium ST responsibility, with the 220 N engine as used within the ATV, and the 500 N EAM engine. This engine is currently in development as the LAE S 400 successor, and would be available for application by 2011 / 2012.

Figure 10: Astrium proposal for a Lunar Lander Module concept with 220 N and 500 N Engines (mock-up model).

Alternative to clustering of available engines /thrusters a throttleable engine concept with a throttle down capability to 10% of the nominal thrust could be considered. Such a concept has to be selected for higher masses of the module to be landed on the Moon.~~,~~ For example the Apollo Descent engine has a thrust of 44,4 kN and the roll control was performed with 441N thrusters, both using bi-propellants. [14]

5. STATUS OF PROPULSION TECHNOLOGIES

In addition to the investigation of a liquid propulsion system for soft and precise landing, 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 a Mars mission, only an adaptation of existing hardware is compliant with in time hardware availability.

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, e.g. Mars-Express 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 (by the spacecraft or by a kick stage). 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. Regarding the tank also the sloshing effect during the descent manoeuvre has to be considered

For missions with ascent such as Mars Sample Return, the weight factor becomes more and more important. Currently only ascent with a propulsion system delivering a performance of Isp > 300 sec 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.

Figure 11 shows the performed screening of the different propulsion technologies and their development potential.

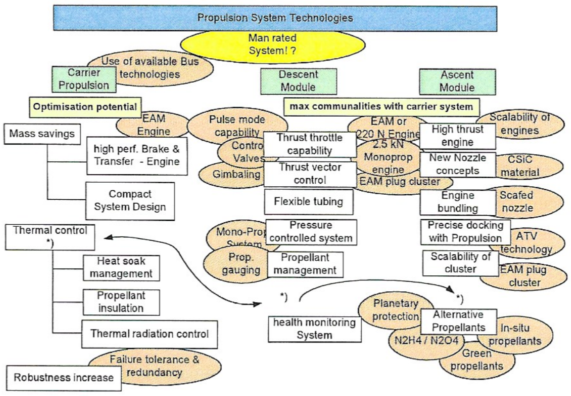

Figure 11: Technology screening.

a) **Carrier propulsion technologies** have the main objectives to transport the "payload" after separation from the launcher to the planet and into its final orbit around the target planet, or to inject 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. The portfolio of thrusters and engines covers a wide range of 10 N, 220 N, 400 N, 500 N (when qualified).

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 (Δv ~ 2000 m/s - 3000 m/s). Lower thrust throttleable engines are required for the final precision approach and soft landing. For the throttleable engine the thrust level requirement foresees a throttling range down to 10 % of the nominal thrust and up to 120% in the upper range. In the case of ExoMars, precision landing requires a total thrust of 2 - 3.5 kN for a landing mass of approx 300 - 400 kg. 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 system level, e.g. the ability of high flow rate components, such as latch valves, to have adequate switching time. At system level, e.g. the ability to control pogo (water hammer) effects.

c) Ascent technology calls for a high performance engines (Isp > 320 sec), either as a single or clustered engine pack. However, the thrust range commences with a thrust level of approx. 8 kN.

The different propulsion needs are characterised in the following Table 2.

Main Engine Requirement	**Carrier Module**	**Descent Module**	**Ascent Module**	Remark
high specific impulse	X		X	high perf. Engine
long steady state firing	(x)		X	
throttle capability				
pulse-mode capability		X		
thrust vaiation down to 15%		X		
fast thrust built up		X		re-ignition capability
constant thrust operation	X		X	
thrust range	400-800	> 3 kN	> 8 kN	depend on landing-ascent mass
planetary protection requierement		only for Mars Mission		

Table 2: 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 some examples out of the wide scatter of available technologies. However, TRL ranges from 2 to 4 and in some cases up to 5 are available. To make existing technologies ready for future robotic missions, the most promising candidates are pre-selected and investigated, within say, the Technology Readiness Programme (TRP). 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 investigated. 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 e.g. ascent applications.

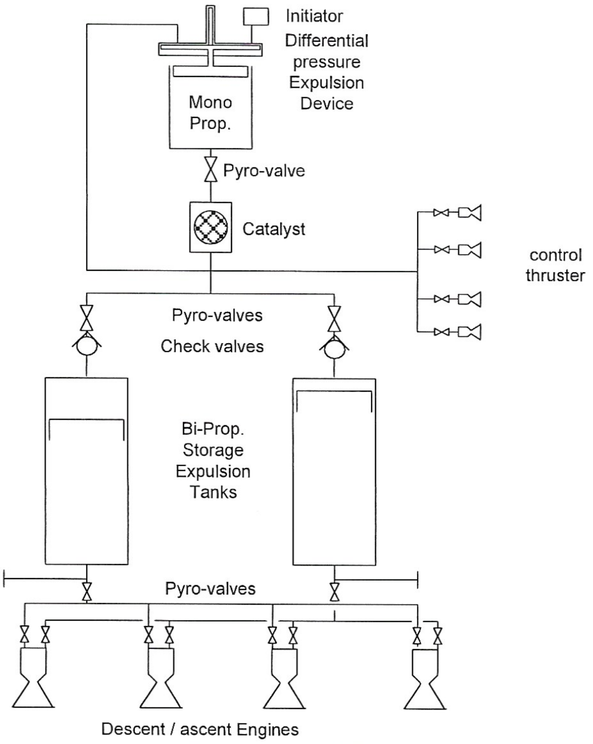

Figure 12: Propulsion system [4].

Another example at systems level is, to reduce the structural mass by changing the classical propellant tank configuration with a separate engine attachment interface by 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.

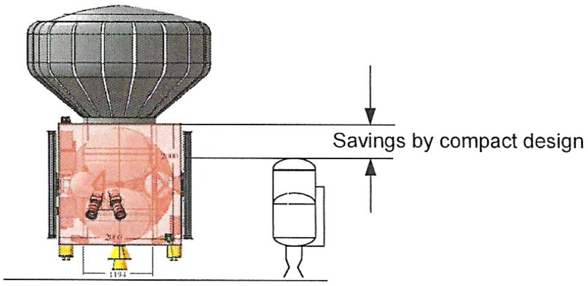

Figure 13: Structure savings by compact tank design

Such a system will save weight and represents a much more compact geometry. Such a compact design could be also used for Telecom, respectively commercial missions when available.

2) Throttleable Engine technology capability

Decent propulsion technology is closely linked with the possibility to vary the thrust during the descent phase. This technology is the preferred one while the pulse operation always implies "shocks" to the payload which gets perhaps critical at the touch-down sequence. Two different types of throttle-capability are possible:

- Step wise- and
- Continuously variable control mode.

The step-wise approach could be realised by thrusters in cluster configuration.

Continuously variable control mode imposes challenges into a storable propellants pressure-fed engine design in view of coolant management, and thrust chamber combustion stability mastering. First, sufficient pressure drop across the injector at all load points including the low thrust level is needed to ensure efficient propellant atomisation, and to ensure sufficient margin against combustion instability. Constraint is given by the maximum available pressure budget, imposed by the tank supply. Following a deep throttling range requirement, an injector design based on variable injection geometry allowing for adjustments in injector pressure drop as function of load point would be needed. Such a system could be realised with the pintle injector.

The heat flux management in deep throttling mode is the second challenge. While throttling e.g. from 100% down to 50% thrust level, coolant mass flow rate decreases linearly with the thrust and thus with the chamber pressure. The combustion chamber heat flux decreases however only from 100% down to 57% due to its dependency $q \sim (p_c)^{0,8}$, asking for specific cooling technologies. Throttleability therefore likely asks for pure film-cooling, or regenerative cooling supported by film-cooling. As consequence, the engine will have a lower combustion chamber efficiency compared to high performance engines with regenerative cooling.

3) The use of a plug engine cluster is an interesting technology prospect [9].

With such a concept, throttleability 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.

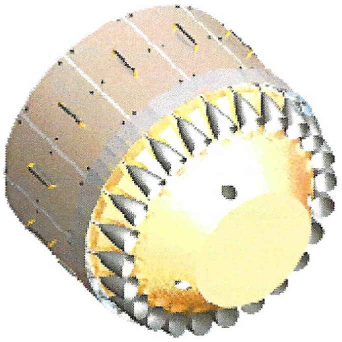

Figure 14: Plug cluster based on 500 N liquid Apogee engines.

4) Single plug engine

Gimballed engines with a high nozzle extension epsilon 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.

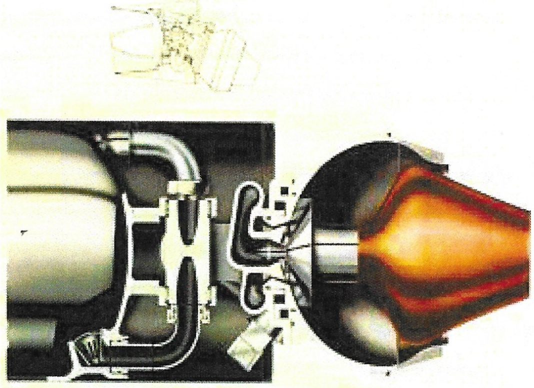

Figure 15: Single plug engine [4].

In addition, the length of the descent engine nozzle is one driving parameter of the landing legs of the vehicle, as it can be seen on Fig [18].
In combination with a pintle injector, mechanically coupled with the plug, the chamber pressure could be kept constant during thrust variation, leading to advantages in combustion efficiency. To demonstrate the technical concept, several seconds of hot fire testing has already been performed. With advanced materials, a plug could be realised to withstand long-term firing durations.

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 engines, with rotatable segmented nozzles, were clustered to achieve thrust vector change.

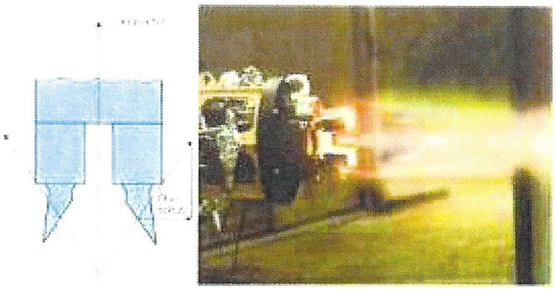

Figure 16: Clustered engines under test firing [4].

6. PROPULSION TECHNOLOGIES APPLICATIONS

Missions to our solar system will gather information through orbital observation and direct contact by robotic operations. Concerning propulsion reliable and robust products are needed. Prior using these products for e.g. a Moon Mission the system shall be tested under flight operation conditions.

Beside the verification possibilities on earth (ground tests and/or test with a demonstrator vehicle on earth, the Earth's Moon is an ideal body to verify the technology first before using them for deep space exploration application. ,

Within a national study a lander to demonstrate descent technologies on Earth is under investigation.

One important objective of investigation is the investigation of soft-landing with pulse-mode operating thrusters to vary the thrust. The investigation concept is based on an engine / thruster arrangement of 500 N engines and 200 N thrusters. The main engines operate in steady state mode only, providing a certain thrust level. The assist engines (e.g 200 N) are operating in a fast pulse mode, currently 2.5 Hz are under investigation to ensure a stepwise throttleable thrust. First tests on the test facilities confirmed the expectations. This interesting concept is a good candidate for the Lander-demonstrator. The demonstrator concept is illustrated in Fig. [17].

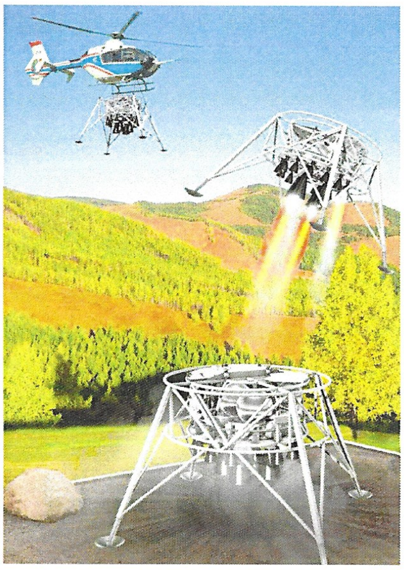

Figure 17: Earth Lander demonstrator concept.

The demonstrator will be lifted up by a Helicopter and will be "set-out". The propulsion system will take over the control of the vehicle and shall demonstrate a soft landing manoeuvre on earth.

In the longer term even a Moon cargo lander is under investigation which could become a good candidate in a potential cooperation between NASA and ESA. This device will be able to land payloads in the order of 1 ton onto the Moon surface. Especially for such a lander the plug nozzle concept as of Fig 14 could be considered [12].

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. Fulfilling both of these braking requirements with a common propulsion concept would currently appear difficult to manage.

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.

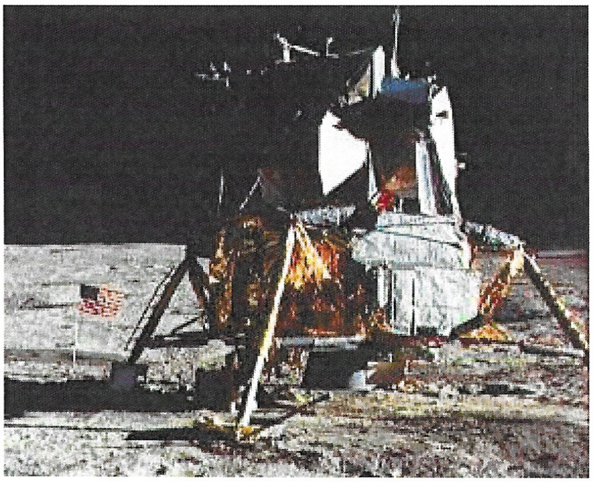

Figure 18: NASA - Apollo 14 Lander [11].

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 throttleable 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 throttleable bi- propellant (NTO/MMH) or dual mode engine (NTO/N2H4). Such engine development shall be proposed for the next ministerial conference 2011. Such engine will demonstrate Europe's willingness to play a major rule within exploration

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

[12] M. Peukert, G. Hageman, B. Mewes, K. Quering: Plug Nozzle Prop. System for a Moon Descent Vehicle, 3AF 42_048, 5th Prop. Conf. 2008

[13] Apollo 14 NASA Natioanl Space Science Data Center; http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-008C.