Development Roadmap and Design of Demonstrators for Hybrid Rocket Propulsion in Europe

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Abstract
Within the EU-funded Operational Research Project on Hybrid Engine in Europe, ORPHEE, a consortium of industry and academia aims to improve the knowledge and understanding of key aspects of hybrid rocket propulsion in Europe. Among detailed theoretical and experimental investigations on propellant combinations and hybrid combustion, one work package within ORPHEE is dedicated to the development of a technological roadmap for the further development of hybrid propulsion technology in Europe and the conceptual design of demonstrator engines. This paper describes the design process and the current status of the demonstrators and the next steps to be taken in a roadmap for the future advancement of hybrid propulsion technology in Europe.

1. Introduction

ORPHEE Program Overview

The EU-funded Operational Research Project on Hybrid Engine in Europe, ORPHEE, has been started to improve the knowledge and understanding of key aspects of hybrid rocket propulsion in Europe. Among detailed theoretical and experimental investigations on propellant combinations and hybrid combustion, one work package within ORPHEE is dedicated to the development of a technological roadmap for the further development of hybrid propulsion technology in Europe and the conceptual design of demonstrator engines. Figure 1 shows an overview on the work logic of the program.

Within a system-level analysis, several potential missions and corresponding hybrid propulsion systems have been investigated [1]. The result of this system level analysis is a set of basic requirements to be demonstrated on subscale level. Results of neighbouring work packages investigating the behaviour of different solid fuel formulations [2] - [7] and advancements in the field of combustion modelling [8], [9] are also taken into account during the design phase for the demonstrators. The design of the demonstrator engines is accompanied by a task which identifies the potential test sites to be used for the demonstrator test campaigns and the works to be performed in order to facilitate the foreseen tests on one of these benches. In parallel, a technological roadmap is developed to guide the next steps of the development of hybrid rocket propulsion systems towards their application.

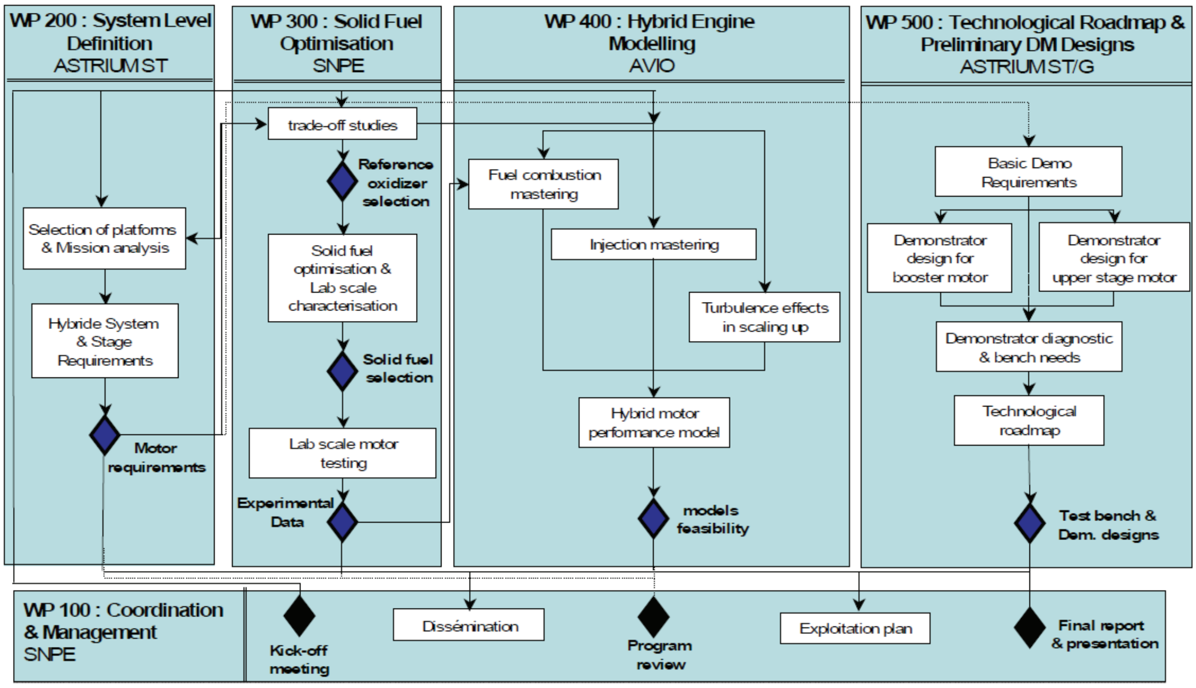

Figure 1: ORPHEE work breakdown structure

Organization of WP 500

Within work package 500, the task of designing a technology demonstrator is split among several partners, Astrium Space Transportation (Operations and Propulsion & Equipment directorates), AVIO and SAFRAN-SME. Two demonstrators are developed: A booster stage demonstrator and a demonstrator for a lunar lander application, allowing to complementary demonstrate the key requirements for booster upper stage and lander applications: High regression rate, high I_{sp}, multiple ignition and deep throttling capability. For both selected applications, Astrium Space Transportation Operations in Les Mureaux set up a requirements file to guide the design of the individual experimental setups. A set of characteristics of different potential test benches in Europe was set up. After having decided to use DLR's P8 test bench for demonstration tests, the relevant design parameters for the two demonstrator engines were derived. In task 520, AVIO is responsible for the system integration of the booster stage demonstrator, whereas Astrium Propulsion & Equipment in Ottobrunn is responsible for the system integration of the lunar lander demonstrator in task 530. Within both tasks, the project partners Astrium, AVIO and SAFRAN-SME contribute to the layout of the demonstrator by designing specific components according to their individual professional background. Astrium defines the liquid propellant feed system and the oxidizer injector, while AVIO and SAFRAN-SME design the fuel grain, its casing and the ignition system.

In parallel to the development of the demonstrators, DLR elaborates the modifications required to eventually test the engine systems on a selected test bench and to demonstrate the achievement of the different test objectives. Potential modifications concern the flow rate capacity of the oxidizer feed system, the data acquisition system or changes required to apply optical diagnostics during the firings.

2. Demonstrator for Hybrid Booster Engine Application

The system level and stage requirements of the booster engine and the lunar lander engine were established in WP 200 by Astrium Operations and handed over to WP 500 for the definition of the demonstrator requirements. A potential application of a hybrid propulsion system is the first stage of a small launcher like Falcon-1 (see Figure 2), which is currently powered by the Merlin LOX-Kerosene gas-generator engine.

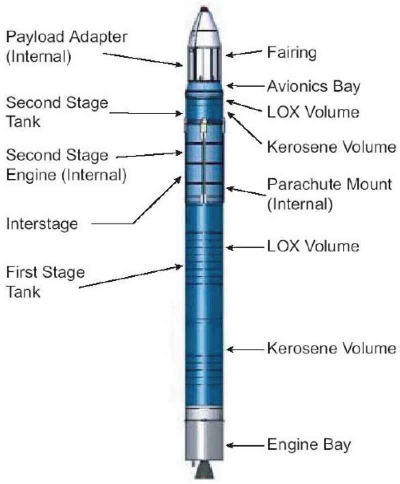

Figure 2: Falcon 1 launcher

System Level Requirements

For the first stage of a small launcher, a stage optimization has been performed by Astrium Operations using the following assumptions:

- Advanced hybrid fuel with improved regression rate
- Liquid oxygen as oxidizer
- Stage diameter same as on original Falcon 1 1st stage
- Mission is transfer to sun-synchronous orbit (800 km x 160 km, 98° inclination)
- Payload mass: 390 kg
- Throttling required to limit maximal acceleration

Table 1: Hybrid first stage performance parameters

	LOX/RP-1 stage	**Hybrid stage**
Propellant mass m_{prop} [kg]	21.087	21.653
Inert mass m_{inert} [kg]	1.296	2.538
Propellant mass flow rate m [kg/s]	190,8	130 - 180
Vacuum thurst F_{vac} [kN]	569	395 - 547
Specific impulse in vacuum $I_{s,v}$ [s]	304	310

Based on the aforementioned considerations, a preliminary design of the hybrid booster stage has been performed (see Figure 3). Table 2 summarizes the key geometry parameters.

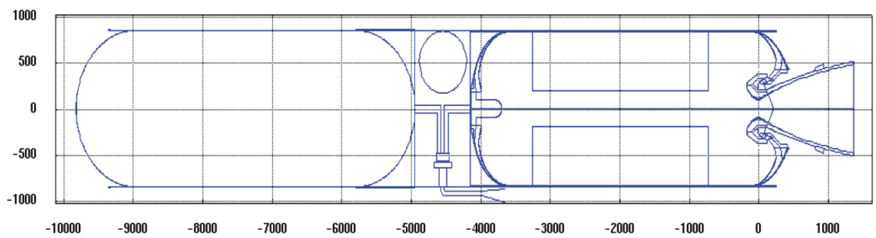

Figure 3: Hybrid booster geometry illustration

Table 2: Hybrid booster geometry parameters

Overall diameter D [m]	1,7
Solid length l_{solid} [m]	5,5
Liquid length l_{liquid} [m]	4,9
Overall length l [m]	11,2
Throat diameter d_t [m]	0,22
Nozzle expansion ratio ε_e [-]	18

Demonstrator Requirements

The demonstrator for the hybrid booster engine shall be designed to be tested on a subscale level on DLR's P8 test bench. Accordingly, some of the full scale requirements were adapted and some additional constraints had to be taken into account. Table 3 compares the requirements and operating characteristics of the booster engine and the subscale demonstrator identified by AVIO. Several aspects are of key importance for the booster demonstrator: A high specific impulse, a high thrust level and a high regression rate. The required throttling capability is not defined as requirement for the booster subscale engine, as this feature is demonstrated on the lunar lander engine on a higher level (see below).
Following this scaling study and design considerations, a preliminary design of the different subsystems was performed.

Table 3: Requirements for hybrid booster demonstrator engine

	Hybrid booster stage	**Hybrid booster demo**
Nozzle area ratio ε_e [-]	18	truncated at sea level
External diameter D [m]	< 1,7	< 1,5
Fuel grain length L [m]	5,5	< 2,4
Burning time t [s]	128	128
Maximum pressure p_c [MPa]	12	12
Average mixture ratio O/F_{mean} [-]	0,97	1
Throttling capability F_{max}/F_{min} [-]	1,4	1[a]
Max. vacuum thrust $F_{vac,max}$ [kN]	600	54
Max. sea level thrust	not specified	50
$I_{SP,vac}$ [s]	310	289
$I_{SP,SL}$ [s]	not specified	265
Average regression rate	5,0 - 5,8	5,6

a: Throttling is demonstrated on lander engine

Demonstrator Design

Based on the requirements, Astrium Propulsion & Equipment and AVIO concurrently designed the hardware components for the booster demonstrator. In addition to the main components fuel grain, LOX injector and nozzle, this task also comprised the design of the interfaces for the ignition system and the interface required to install the test specimen on the test bench.

The design of the fuel grain and the nozzle is shown in Figure 4. The fuel grain has a length of approximately 1,6 m, an initial inner diameter of 0,136 m and an outer diameter of 0,5 m. It is installed in a casing, which realizes the interface to the injector head and which also comprises the post-combustion chamber and the submerged nozzle. In contrast to the foreseen real application, the possibility of thrust vector control was not realized on the demonstrator setup. The expansion nozzle is truncated at sea level.

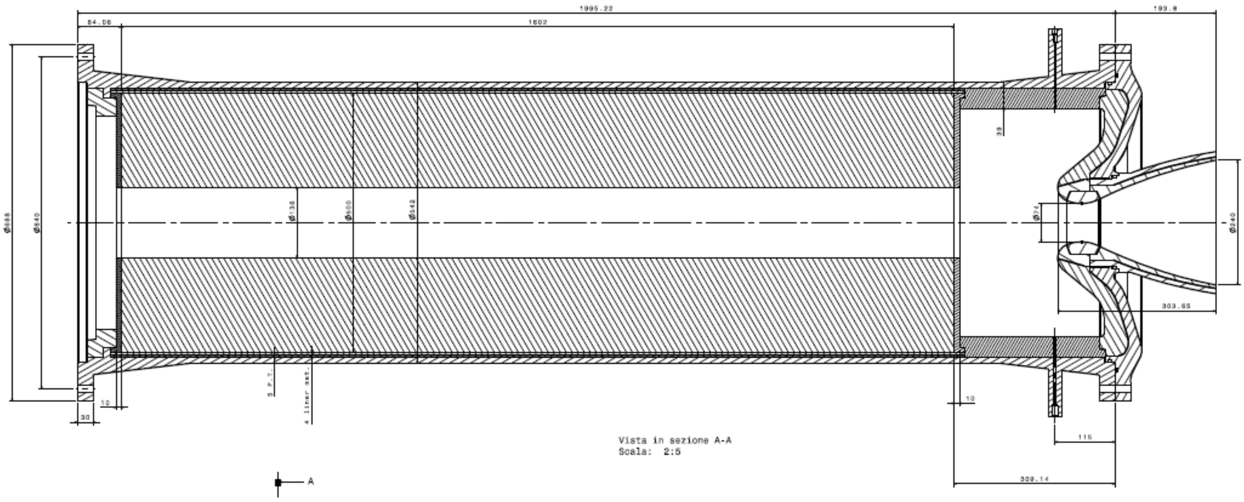

Figure 4: Hybrid booster demonstrator fuel grain and nozzle

The design of the injector head is shown in Figure 5. Astrium Propulsion & Equipment selected and designed a so called curl injector, which injects the liquid oxidizer through two rows of orifices. This stepwise injection of fluid is designed to provide a most possibly homogeneous distribution of the oxidizer over the length of the chamber. As the injection angle not only depends on the orientation of the orifices and the injected fluid mass flow but also on the geometry of the combustion chamber and the flow velocity in the chamber, it can be designed such that the changing LOX trajectory matches the regression of the fuel grain during operation as illustrated in Figure 6 and Figure 7.

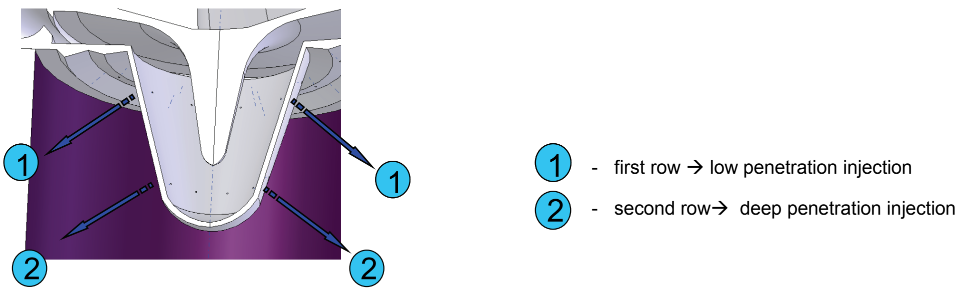

Figure 5: Hybrid booster demonstrator injector concept

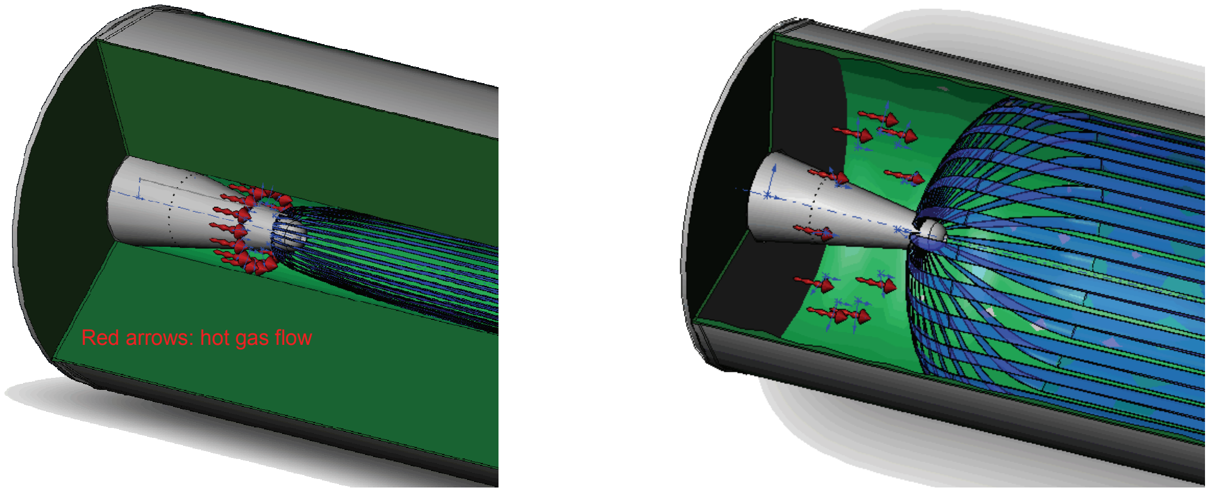

Figure 6: LOX trajectories of 2nd injection row at beginning (left) and end (right) of operation

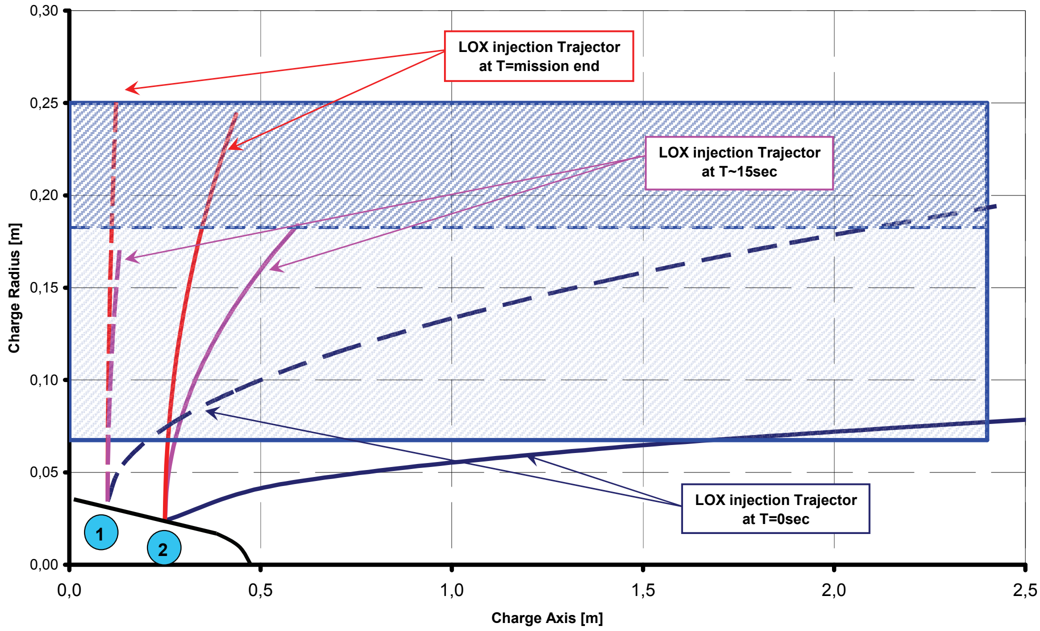

Figure 7: LOX droplet trajectories for different operating times

The injector design allows for the integration of a gas torch ignition system as is it used typically on the P8 bench. The igniters hot exhaust gases are fed through a bore in the center of the injector. Specially designed deflectors ensure that the hot gases are directed to the surface of the fuel grain, ensuring a reliable ignition. Figure 8 illustrates the integrated design concept of the booster demonstrator including the interface to the test bench and the gas torch igniter.

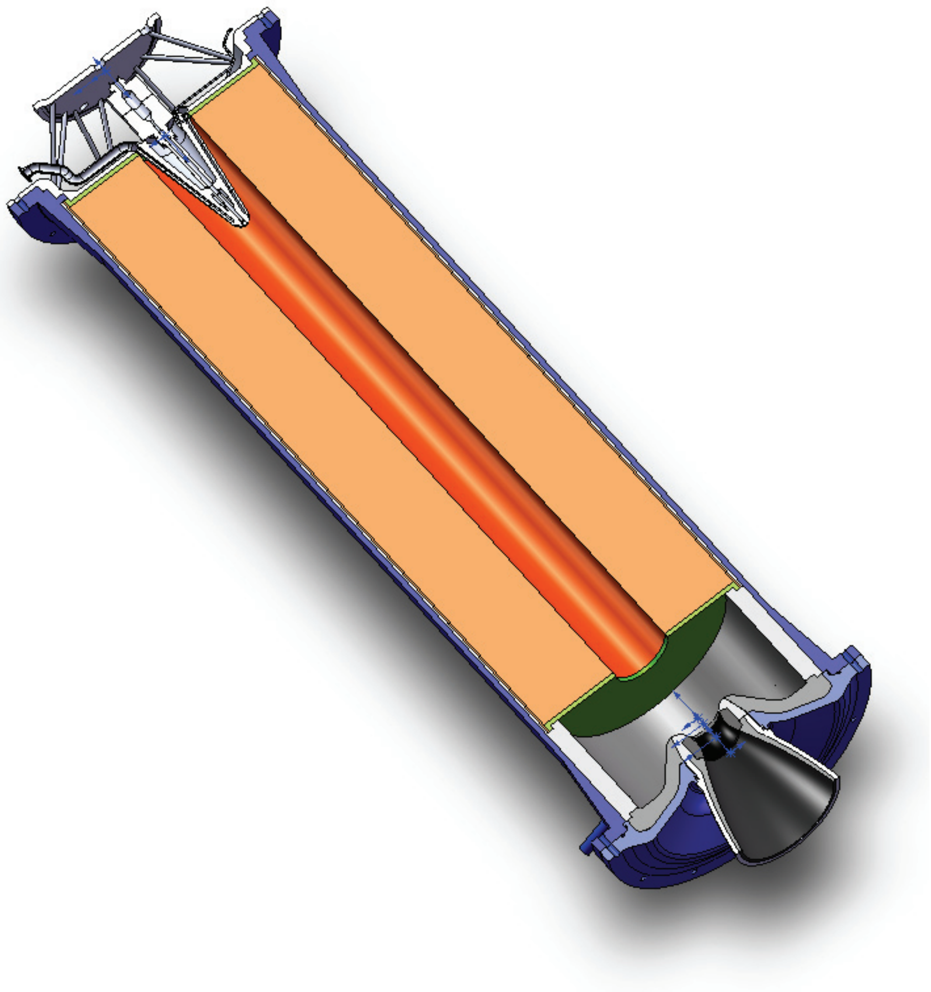

Figure 8: Booster demonstrator design

3. Demonstrator for Hybrid Lander Engine Application

As for the hybrid booster, a detailed mission analysis performed in WP 200 provided the starting point for the design activities for a hybrid engine for the application in a lunar lander vehicle. The lander's propulsion system should allow to perform a soft landing descending from a 100 km circumlunar parking orbit. The initial vehicle mass was assumed to be 2.000 kg. The descent is organized in three boost phases:

1. Deorbiting from circular 100 km orbit to 100 x 10 km orbit → Δv = 20,6 m/s
2. Deorbiting from 100 x1 0 km orbit to 10 x 0 km orbit → Δv = 23,3 m/s
3. Deceleration and hover mode 30 m above moon surface → Δv = 1682 m/s

System Level Requirements

The propulsion system of the lunar lander should meet the following requirements:

- Multiple re-ignition capability
- Deep throttling for soft landing

The landers propulsion system consists of four engines, one central engine operating at fixed thrust and three engines arranged equidistant on a certain diameter operated at variable thrust (see Figure 9). All engines are operated in pressure fed mode. Figure 10 illustrates the flow schematic of the propulsion system's oxidizer feed system.

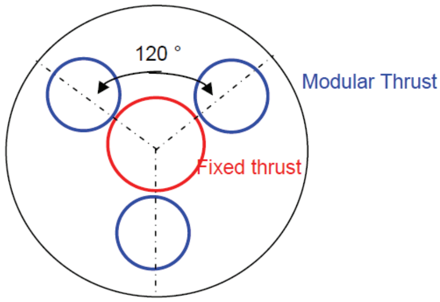

Figure 9: Hybrid lander engine configuration

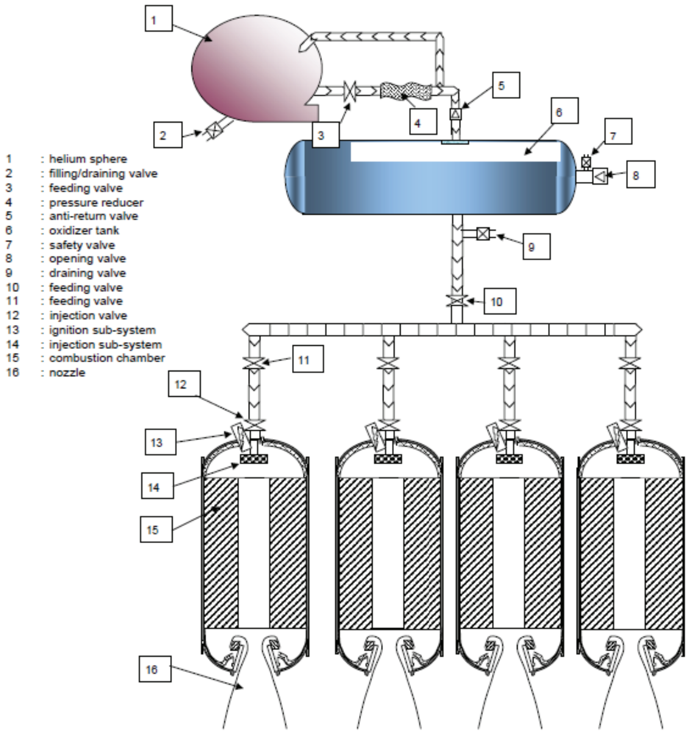

Figure 10: Hybrid lander engine flow schematic

A preliminary design of the lander propulsion system has been performed by Astrium Operations in order to derive key characteristics and requirements for the two engine types employed in the system. Table 4 summarizes the characteristics of the propulsion system's preliminary design.

Demonstrator Requirements

A comparison with the P8 bench capabilities showed that both engine types of the lander propulsion system can be tested in full scale, although geometric constraints prevent the installation of the entire propulsion system on the bench. It was decided to elaborate a more detailed design concept for the exterior engine type. This allows for demonstrating additional key requirements completing the aspects demonstrated on the booster engine:

- Multiple re-ignition capability
- Deep throttling capability

Therefore, the parameters listed in Table 4 were used as target values and constraints of the demonstrator design. Of course, the expansion ratio of the nozzle was adapted to sea level conditions.

Table 4: Characteristics of hybrid lander propulsion system

Parameter	**Central Engine (1)**	**Exterior engine (3)**
Overall diameter D [m]	0,67	0,54
Solid length with nozzle l_{solid} [m]	2,07	0,93
Overall length l [m]	2.075	926
Throat diameter d_t [m]	0,07	0,05
Pressure p_c [MPa]	3	2
Average mixture ratio O/F_{mean} [-]	1	1
Nozzle expansion ratio ε_e [-]	80	80
Propellant mass m_{prop} [kg]	1378	
Inert mass m_{inert} [kg]	279	
Propellant mass flow rate m [kg/s]	7	0,4 - 2,3
Vacuum thurst F_{vac} [kN]	24	1,1 - 8
Throttling capability F_{max}/F_{min} [-]	1	7,3
Specific impulse in vacuum $I_{s,v}$ [s]	350	300 - 350
Accumulated burn time t_{Burn} [s]	100	123

Demonstrator Design

Like for the design of the booster demonstrator, Astrium Propulsion & Equipment and AVIO shared the work to design the lander engine demonstrator.
The design of the fuel grain is based on sizing considerations performed by Astrium Operations and SAFRAN-SME. It aims at highest possible similarity with the design of the booster demonstrator to allow for an easy exchange or re-use of individual components.
The design of the injector has to meet very demanding requirements with respect to the throttling capability of the setup. Casiano et al. summarized in their publication different generic methods to provide sufficient spray quality of liquid injectors in a wide operating range [3]. Astrium Propulsion & Equipment decided to benchmark the following technologies:

- High pressure drop injectors
- Variable area injector
- Dual manifold injector
- Gas injection

In a pressure fed cycle, the injector pressure drop has to be limited in full operation. At low mass flow rates, this would result in poor spray preparation, if no additional measures like variable area and/or gas injection were implemented. Variable area, dual manifold and gas injection can be applied to different injection concepts. A trade-off study for the following concepts was performed:

- Swirl injector with variable geometry
- Swirl injector with gas injection
- Curl injector with dual manifold
- Curl injector with gas injection
- Pintle with variable geometry
- Pintle with variable geometry and gas injection

The result of the trade off, which took into account aspects like combustion stability, combustion efficiency, system complexity and the possibility to integrate the ignition system, is shown in Figure 11. A pintle injector with variable geometry was selected as most appropriate solution in view of the requirements list (Table 4). Figure 12 shows a preliminary design of a pintle injector equipped with a splash screen.

As next steps, Astrium Propulsion & Equipment will perform a detailed design of the injector head and integrate this into the fuel grain design provided again by AVIO.

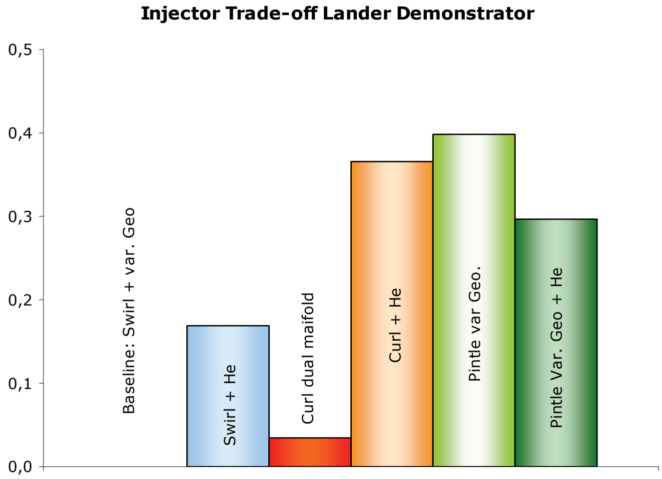

Figure 11: Hybrid lander LOX injector trade-off

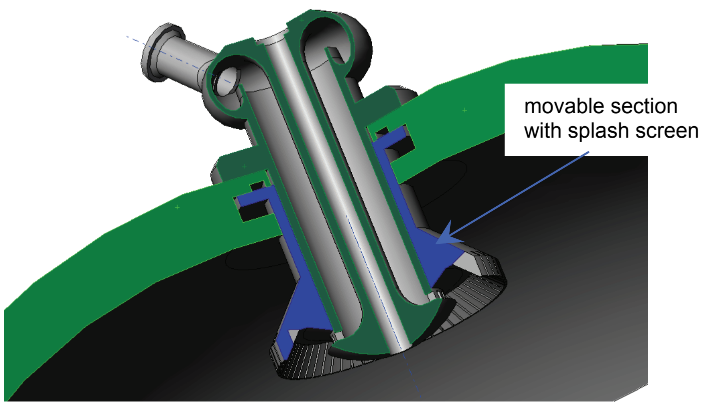

Figure 12: Hybrid lander pintle injector

4. Development Roadmap

As the work in all the different work packages of ORPHEE progresses, key issues were identified which will be the starting point for a development roadmap for further increasing the level of maturity in hybrid technology within Europe. The development roadmap will be worked out and will address the following issues:

- Identify key technology drivers with related development and maturation needs for:
  - Solid fuel formulation and liquid oxidizer system
  - Hybrid propulsion system components and equipment (ignition system, motor casing, nozzle, power pack, etc.)
  - Hybrid propulsion system testing requirements and capabilities (e.g. systems for pressurization, ignition, gimbaling, altitude simulation...)
  - Hybrid propulsion component and system modelling capabilities (e.g. injection, combustion, performance analysis etc.)
- Establish a high level technology roadmap including rough activity scheduling

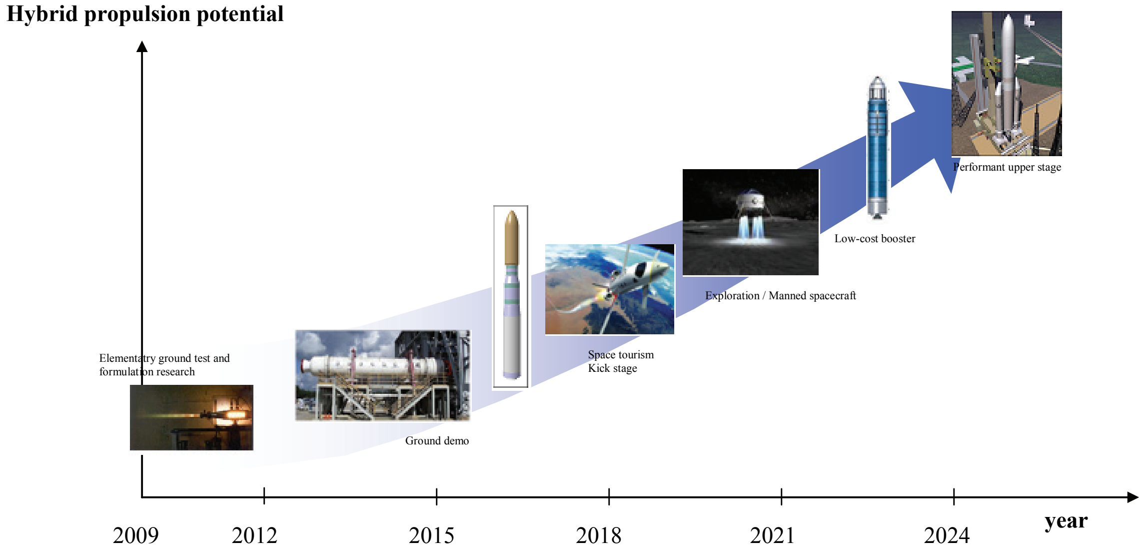

Figure 13: Hybrid propulsion development roadmap

5. Conclusion

The EU-funded Operational Research Project on Hybrid Engine in Europe, ORPHEE, has been started to improve the knowledge and understanding of key aspects of hybrid rocket propulsion in Europe. Among detailed theoretical and experimental investigations on propellant combinations and hybrid combustion, one work package within ORPHEE is dedicated to the development of a technological roadmap for the further development of hybrid propulsion technology in Europe and the design of demonstrator engines.

Based on system studies, two engine applications have been chosen for the design of demonstrator engines, a hybrid booster stage of a small launcher and a hybrid lunar lander engine. The demonstrator requirements are floored down from system level studies performed in another work package. The design tasks are shared among the partners SAFRAN-SME, AVIO and Astrium, with each partner taking responsibility according to its key competences. Testing of the two setups will allow demonstrating specific requirements like re-ignition capability, high thrust (i.e. regression rate), I_{sp} and throttling capability.

6. Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n°218830. More details on ORPHEE can be found under http://www.orphee-fp7-space.eu/index.html.

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