Main Stage Liquid Propulsion Activities within Europe's Future Launcher Preparatory Programme FLPP

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Abstract
Objective of the FLPP programme is to prepare Europe for the decision on its Next Generation Launcher within the next years to come. With the current programme status, both reusable and expendable concepts are studied. Facing Europe's heritage on expendable launch vehicles, it has been decided to concentrate the initial effort towards reusable concepts and on key-enabling technologies meeting ambitious vehicle and its subsystem service life requirements. A requirement driven development approach has been adopted to define the propulsion system requirements and to derive the further need for technology demonstration by ground tests. Three reference engine concepts have been worked out by the propulsion consortium, one for each fuel combination Hydrogen, Methane and Kerosene. Specific technology work has been started on identified critical subsystems, including turbopumps, valves, staged combustion devices, and health monitoring systems.

1. Introduction

The European Future Launcher Preparatory Programme, FLPP,[1] focuses on a sound and comprehensive proposal preparation for the Next Generation Launcher, NGL, on both programmatic and technological levels, with the following key objectives:[1], [2]

- To maintain the guarantee of an affordable and European independent access to space in the long-term;
- To respond to growing European institutional diversified launch service needs stemming from the building-up of the European Union and the implementation of European policies (environment, security, defence, etc); and
- To capture a significant share of new commercial markets, which are dependent on the reliable and cost-effective access to space.

FLPP targets the proposal for the NGL system by 2014, with the NGL becoming operational not before 2020-2025. From today's perspective, both Reusable Launcher Vehicle, RLV, and advanced Expandable Launcher Vehicle, ELV, systems are potential candidates for the NGL. The focus of the first FLPP programme period (starting from 2004) is the down-selection among various RLV concepts driving the further technology development by 2008. The second period to be started in 2007, focuses on the down-selection among various ELV concepts with the same technology development target. In this 2nd period, the possible evolution of current ELV towards cost reduction will be also identified. It is further foreseen to consider then the selected RLV and the advanced ELV in more detail until 2014; thereby preparing and enabling the key decision among ELV and RLV for the final FLPP programme step: the start of the NGL development.

This paper discusses the scope and status of the liquid propulsion activities within FLPP:

- Studies are performed at reusable engine system level to support the choice of the propulsion system, the definition of the high level requirements, the test conditions in the various technology areas, and to progress in the design methodology for a reusable engine. Reference engine architectures have been defined for the three

[1] The ESA FLPP Programme is managed by the prime contractor NGL Prime SpA Company. Liquid propulsion system and technology activities are subcontracted to the Joint Propulsion Team, JPT, a consortium between Snecma Sagem, Astrium Space Transportation and Avio SpA.

different propellant combinations being identified as option for the next generation reusable launch system, LOX/Hydrogen, LOX/Methane and LOX/Kerosene.

- Technology development activities are defined for LOX/Hydrogen and LOX/Hydrocarbon engines, also keeping in mind the possible synergies with ELV liquid engines especially from the reliability and performance point of views. Special emphasis is put on high performance cycles (e.g. staged combustion) and reusability focusing on reusable engine components (igniters and valves), turbopump, long life combustion chamber, preburners, nozzle extension, turbines, and health monitoring systems.

The focus of the paper will be the technology discussion for turbopump, and combustion devices. The technology development includes hardware manufacturing and tests at relevant scale to assess and demonstrate key enabling technologies for real RLV propulsion system. To address the technology effort conducted for valves and health monitoring, the interested reader is referred to literature, see Ref. [3], [4].

2. Propulsion Requirements derived from RLV Launcher Studies

NGL Prime SpA reviewed all existing RLV launcher concept study results, with data available from public domain, and in detail concepts proposed and investigated in national programmes of France and Germany. This data is reflected against two consolidated mission requirements:

- Reference mission #1 (RM1) to geostationary orbit covering the market of commercial heavy telecommunications satellites (towards 7.5 tons in GTO).
- Reference mission #2 (RM2) to low Earth orbit covering the European institutional needs for medium to heavy payloads (5 tons in SSO-700 km).

The mission requirements were formulated by the European Space Agency based on market trends and forecasts, as well as satellite mass trends. The RLV launcher review included criteria on yearly launch rates, launch and landing sites, payload accommodation, dependability and safety, and fleet size. Based on these trade-off criteria, TSTO, RFS, and SOH were selected to be promising concepts. Based on this first trade-off among the launch vehicle candidates preliminary high level requirements were derived for propulsion system studies as listed in Table 1.

High level requirement	LOX/Hydrogen	LOX/Methane	LOX/Kerosene
Vacuum thrust	2000 kN	2000 kN	2000 kN
Mass	< 3200 kg	< 3100 kg	< 3000 kg
Mixture ratio nominal	6	3.5	2.78
Mixture ratio range	5.5 – 6.5	3.0 - 4.0	2.2 - 3.0
Specific impulse (orbiter), in vacuum	> 448 sec.	--	--
Specific impulse (booster), in vacuum	> 435 sec.	> 345 sec.	> 335 sec.
Reusability	25 flights	25 flights	25 flights
Throttleability	50% - 100%, 120%[2]	50% - 100%, 120%	50% - 100%, 120%

Table 1: High level system requirements for the rocket engine propulsion system.

3. RLV Reference Engine Definition

The reference engine definition for the NGL is twofold; the first steps include the reference engine definition within the propellant combinations followed by the second step, including the final reference engine definition among the different propellant combinations considering the system level requirements of the NGL.

The first reference engine definition includes the identification of major technical requirements of rocket engine systems with primarily focus on high reliability and performance, the assessment of enabling reuse technologies needs and the establishment of a roadmap to achieve an TRL of 5 by 2010. Further included are the thermodynamic analyses of possible rocket engine architectures, and the generation of a decision database to conduct a cost-benefit-analysis for the reference engine trade-off.

[2] 120% for engine out-capability, EOC, depending on launcher configuration.

Details of the performed TRL assessment and trade-off are included in Ref. [3]. Among the engine cycles, gas-generator and staged combustion cycles were considered. The final engine choice for a given propellant combination was performed by a cost-benefit analysis, while the final choice among all three propellants has still to be performed on launch vehicle level.

3.1 LOX/Hydrogen RLV Reference Engine

The gas generator cycle performance figures remain below the FLPP engine requirements; thus, it was only further considered as reference for the cost-benefit analysis.

In a cryogenic engine, the HPFTP is a very high power subsystem (roughly 40 MW in the considered staged combustion architectures) and therefore the more critical subsystem aside the MCC. For example, during SSME development, five critical events occurred mainly on this subsystem (turbine blade failures and sub-synchronous whirl) and in the Block B configuration the HPFTP has to be dismounted after ten flights. As limitation, the staged combustion calculations are performed at a fixed HPFTP outlet pressure of approx. 400 bar (HPFTP head rise (pressure increase) is respectively 430 and 420 bar for SSME and RD-0120) at a rotational speed of 36000 rpm.

The engine cycle analyses result in a combustion chamber pressure close to 150 bar for all fuel-rich and for the full-flow staged combustion engine cycle meeting the performance requirements. It turned out that the fuel-rich staged combustion engine with a single preburner and a dual shaft parallel turbine offers the highest benefit. Figure 1 illustrates the chosen engine cycle and depicts the engine layout.

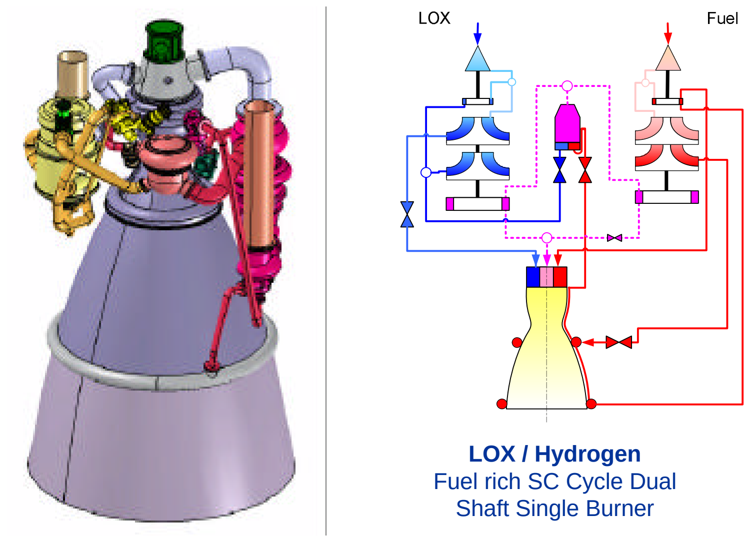

Figure 1: LOX/H2 reference engine architecture.

3.2 LOX/Kerosene RLV Reference Engine

The gas generator cycle is not able to meet the performance requirements; thus, it was only further considered as reference for the cost-benefit analysis. A fuel-rich gas generator cycle was chosen here as reference cycle.

All staged combustion engines were designed for pure ox-rich preburners. All fuel-rich preburners were discarded due to the risk of soot production within the exhaust, which may cause blocking of the hot gas injection elements of the injector head for the main chamber. This in fact also excluded the full-flow staged combustion.

The engine cycle analyses result in combustion chamber pressures close to 200 bar for all staged combustion engine cycles in order to meet the performance requirements. Further, from the cost-benefit analysis the best ratio was achieved for the ox-rich staged combustion engine with single burner and single shaft turbopump. This turbopump arrangement is promoted by the roughly similar densities of both propellants. Prominent example of this turbopump architecture is the Russian RD-170 / 180 / 191 family, or the NK-33 / 34. Figure 2 illustrates the chosen engine cycle, and depicts the engine layout.

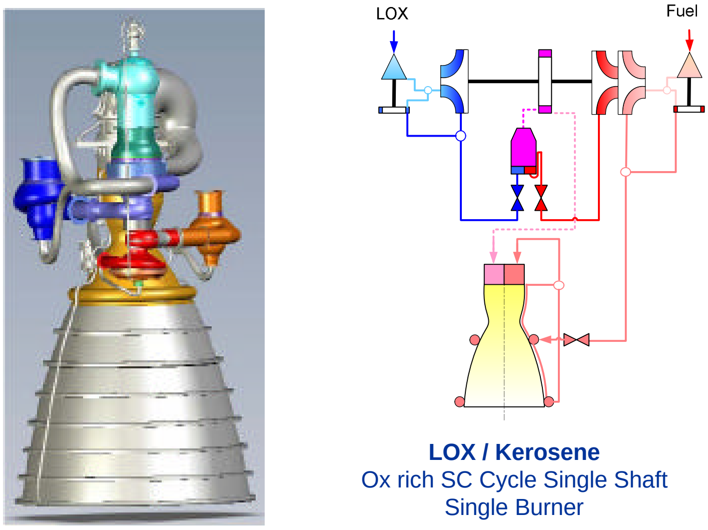

Figure 2: LOX/Kerosene reference engine architecture.

3.3 LOX/Methane RLV Reference Engine

As for the previous two propellant combinations, it turned out that the LOX/Methane gas generator cycle is not able to meet the performance requirements. The further analyses concentrated on different fuel-rich and full-flow staged combustion architectures.

Similar to LOX/Hydrogen, the engine cycle analyses result in combustion chamber pressures close to 150 bar for all staged combustion engine cycles in order to meet the performance requirements. Further, from the cost-benefit analysis the best ratio was achieved for the full-flow staged combustion engine followed by the fuel-rich staged combustion engine with single burner and dual shaft turbopump with parallel turbines. Finally, the rather ambitious full-flow staged combustion engine was chosen with regard to overall lower system pressure (here with focus on the HPFTP, meeting the limitations as defined for the LOX/Hydrogen system). Further, this engine cycle offers best growth potential. It is thereby recognized that this engine cycle is currently also investigated in the “Integrated Powerhead Demonstrator”, see e.g. Ref. [5]. Figure 3 includes the chosen engine cycle, and depicts the engine layout.

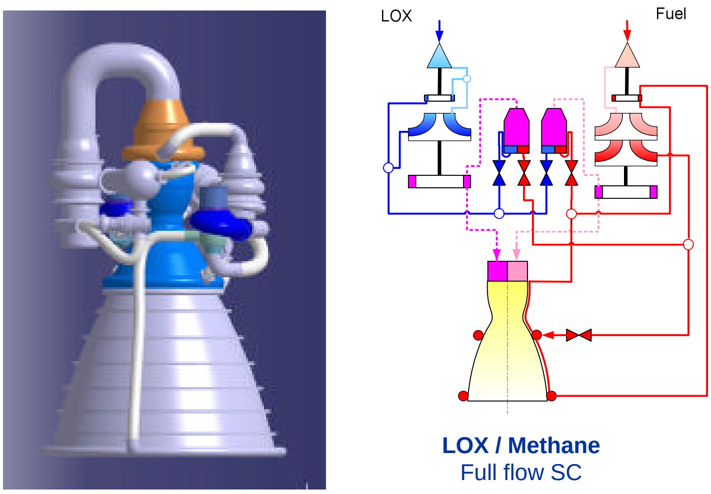

Figure 3: LOX/Methane reference engine architecture.

4. Needs for Liquid Rocket Engine Technology Development

European heritage is built on gas generator engines such as HM-7, Vulcain, and Vulcain 2, the latter being today’s highest performing gas generator engine in operational launch service worldwide. Vinci, the expander-cycle upper stage engine, started successful engine tests in 2006, and documents European competence in the field of closed cycle engines. It has to be recognized that European heritage on staged combustion engines is limited to the technology demonstrators and demonstration programmes, such as

- P111,[6] designed and built by Messerschmitt-Bölkow-Blohm, MBB (today Astrium Space Transportation) from 1956 to 1967 for LOX/Kerosene. This technology engine included experimental demonstration of still today state-of-the-art and even outstanding technology such as
  - Ox-rich preburner;
  - Single shaft turbopump, axially integrated with preburner and main chamber;
  - LOX-regenerative cooled main chamber;
  - Copper liner with milled cooling channels, electro-deposited copper and nickel close-out.
- RECORD, ESA/EU Snecma/CADB programme for RD-0120 testing.

Reflecting this limited knowledge database on staged combustion engine systems in Europe and facing the performance needs demanding for staged combustion, it is obvious that this gap between -what is available - and -what is needed - has to be filled successfully. Thus, relevant knowledge has to be made available.

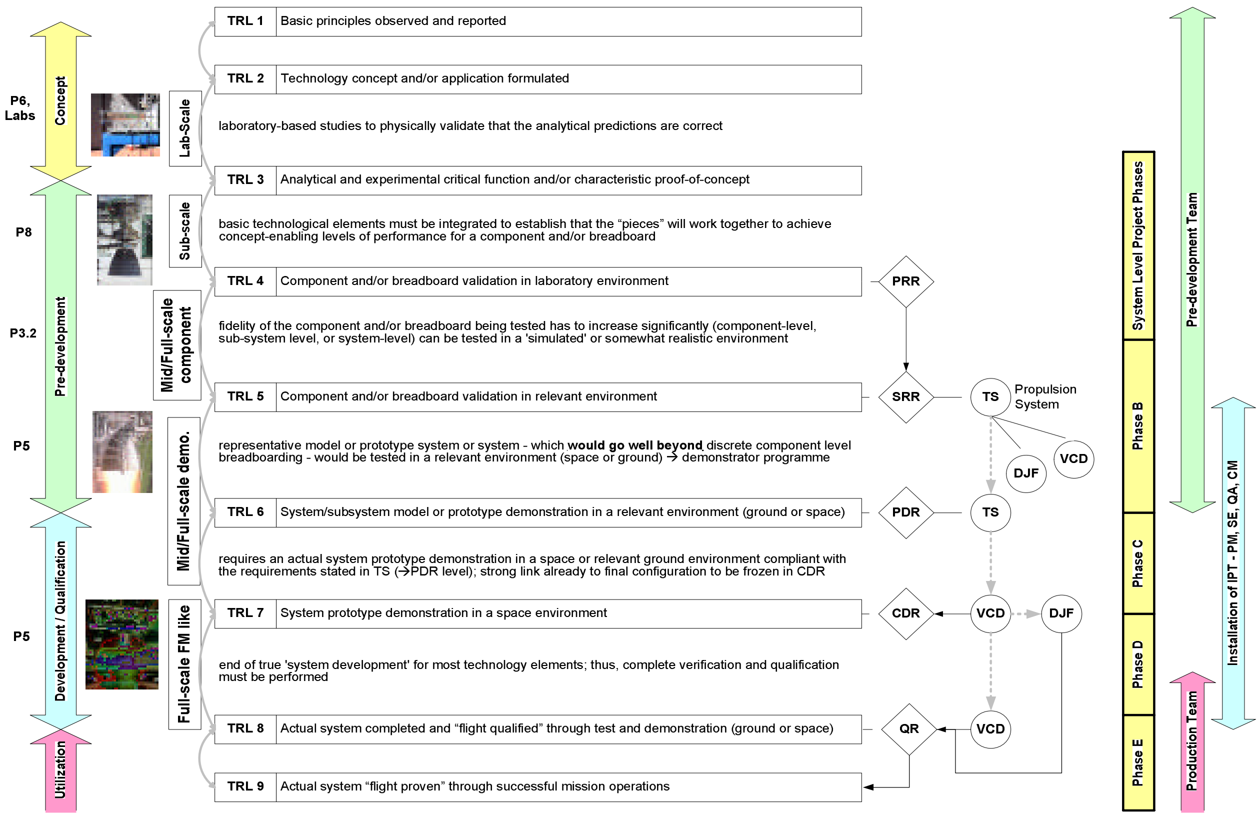

Figure 4: Logic for Technology Readiness Level, TRL, as applied to FLPP technology tasks.

In addition to high performance needs, it is noted that the engine must be designed for use over a large number of missions. Consequently, this requirement implies the development of long-life components and sub-systems, such as simplified and more robust turbomachinery, gas generator/preburners, reusable igniters, new types of injectors, long-life thrust chambers, long-life valves, advanced nozzle extensions, and the demonstration of their life limits both for low cycle and high cycle fatigue. A high degree of reusability is clearly linked to increased time between scheduled maintenance, reduced operation costs, low turn-around times and, in the end, to the vehicle availability. Within FLPP specific technologies are further explored thereby increasing the TRL towards 5, being discussed in the following specifically for turbopumps and combustion devices. Figure 4 illustrates the TRL logic, showing that a TRL of 5 - a level of 6 preferred - is required enabling the start of a full-scale development programme. Consequently, the following key technologies are adopted within the FLPP programme

4.1 Turbopump Technology Work

The most promising activities on turbomachinery, to face problems related to high reliability for reusability, is certainly the development of new concept in the shaft support devices. So far, in the field of expandable launchers, ball bearings had been showed very good performances, also for very high speed rotating machines (e.g. special bearings with ceramic rolling bodies). Unfortunately the life time of such devices cannot support the requirement to have more missions (the challenging FLPP goal is to reach 25 flights with the same hardware) without any major refurbishment.

Envisaged research for solution, which Snecma (for LH_2) and Avio (for LOX) are running along, is to place fluid in the place of rolling supports, basing their design on “non conventional” materials (SSiC, SiC/SiC, Si_3N_4) with more resistant wear capability and very low friction coefficient. Hydrodynamic journal bearings have been found not suitable for the scope, being the fluids viscosity very low, also in the case of High Pressure Turbopumps for LH_2 where the rotational speed is very high compared with the LOX ones.

Hydrostatic bearings have the right capability to support radial loads using the same pressure generated by the pump. The only point is that, during starting phase, the pressure has not been generated yet, and the rotor of journal bearing is rubbing on the relevant stator part: it is evident that this situation requires a very low friction coefficient to reduce the starting torque required to the turbine.

In this field some steps have been initiated by Avio, with a FAST 2 test campaign for metallic journal bearing in LN_2 environment giving good results.

But the most promising test campaign is foreseen in FLPP, where hydrostatic JB are envisaged to be fit into a Vinci class turbomachinery for a subsequent test bench campaign in LOX, including a dedicated device for axial loads support: ABS (Axial Balancing System). The difficulties to face are not trivial: for both systems the transient phases (start up and shut-off) are critical because of friction and the coupling of ceramic material with metallic one (Inconel 718) is difficult due to high difference in thermal expansion coefficients. For the time being we are in the phase of design and accommodation of support devices in already built TPO housing that, from the point of view of time consuming is surely more efficient but from the configuration point of view introduces the difficulties relevant to place something new in a "old" casing. Planning today is to design and to manufacture the parts within the end of the Period 1 Phase 2 of FLPP and to assemble and test the TPO in the next phase.

In the frame of turbomachinery, other activities are foreseen in the FLPP, like studies on Methane as fuel for booster engines equipping the NGL. For this scope, Avio planned some preliminary design studies on entire turbopump configurations (including hydraulic turbines studies) and in particular the design of an axial first stage of the pump (inducer) working in liquid Methane with the idea to test it in the Colleferro facility in the next phases of the FLPP Programme.

The other fields of FLPP technology development are presented hereafter:

1) Dedicated activities regarding the axial balancing system (ABS) aimed to prevent axial bearing overloading are undertaken within FLPP. The goal is to obtain a safe behaviour of ABS compatible with engine transient, bearing capabilities and turbopump mechanical evolution.

2) Due to high tip speed required for pressure head secure, impeller topic for LH_2 turbopump is also subjected to FLPP development works. Indeed, evidences of local stresses have been documented in the past as the result of mainly centrifugal stress, but also dynamic loading. As a matter of fact, the shroud can be considered as the weak point of high performance impeller, limiting LH_2 stage to about 150 bar. This fact leads to study the design of unshrouded impeller for higher tip speed and therefore, higher pressure rise achievement. To face with the specificities of an open impeller, ABS system has to present large margins in terms of both static and dynamic load capacity. In particular different concepts of thrust axial bearing are under evaluation. Even if preloaded ball bearing is classically operated during transient and steady-state regime on most engines, alternative concepts with clutching device were designed considering specific ABS activation speed constraints. A clutching thrust bearing is today the preferred concept to also meet with long life duration and reusability targets: dedicated testing is planned through the advanced R&T CNES/Snecma TP demonstrator called TPTech. Figure 5 shows a photograph of the TPTech demonstrator.

3) An advanced Helium-free concept of dynamic seal package for pump sealing has been designed and will be tested as a first evaluation through TPTech demonstrator, too. Main interests come from the cancellation of classic helium barrier, making possible simplified operation. Wear prevention as well as advanced design make possible improvements in reliability by avoiding drop in sealing performance during operation.

4) Due to the high-rotating speed, high head, and low NPSP requirements some dedicated FLPP development activities are focused on the inducer mechanical and hydraulic design. Inducer design and tests in water and liquid Methane environment are planned through FLPP.

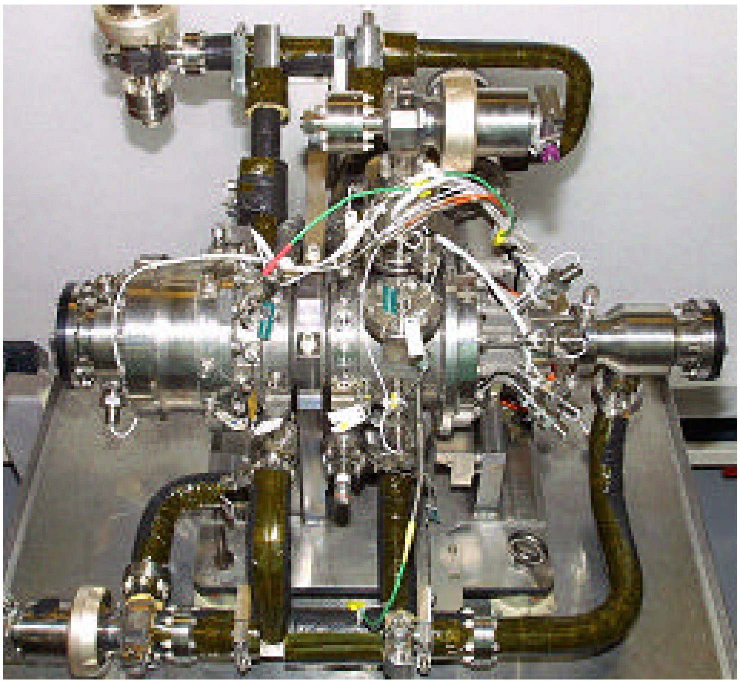

Figure 5: TPTech turbopump demonstrator.

5) The design of a reusable turbine has to face contradictory challenges, which are both high performances and mechanical resistance. For engine performance concern, high pressure and high temperature turbine gas are required. It is well-known that such operating conditions are unfavourable to reliability as well as life-duration.

6) Turbine stators have to withstand temperature spikes at each preburner start-up. It results that material mastering as well as transient profiles control remain critical items of any reusable, high-performance turbine. FLPP activities are also oriented toward the evaluation of classic material limitations and alternative material (with or without coating) capabilities with regard to staged combustion operational constraints.

4.2 Staged Combustion Technology Work

Key objective of this task is to acquire experience and knowledge on staged combustion cycles through the design and operation of a staged combustion pathfinder demonstrator. The demonstrator will focus on fuel-rich staged combustion for LOX/Hydrogen and LOX/Methane propellants. Through FLPP, LOX/Kerosene is not considered for this technology demonstration, because a complementary effort has been conducted within the German / Russian Technology Programme TEHORA, Ref. [7].

The functional characteristics of the staged combustion pathfinder are summarised in Table 2. The operational domain reflects the technical needs derived from the reference engine definition. It is noted that LOX/Kerosene is included here in this Table for information only. For more information, the interested reader is referred to Ref.[7].

Snecma and Astrium-ST jointly contribute to this staged combustion pathfinder. Snecma's hardware responsibility is the preburner chamber with three injector head variants. Astrium-ST's hardware responsibility is the main chamber, also with three hot gas injector variants. Specific injector heads are foreseen for LOX/Hydrogen and LOX/Methane, while chamber bodies for both preburner and main combustor are verified for dual-use. Two different main chamber bodies will be used for the demonstrator: a calorimeter chamber for measuring the axial heat flux evolution and an integral chamber body for the highest load point operations. Figure 6 illustrates the pathfinder hardware set-up and shows also the calorimeter thrust chamber.

	LOX/Hydrogen	LOX/Methane	LOX/Kerosene [3] (for information only, not in FLPP)
Thrust level	55 kN	55 kN	65 kN
Main chamber pressure	max. 150 bar	max. 150 bar	max. 80 bar[4]
Main preburner pressure	max. 200 bar	max. 200 bar	max. 130 bar
Main chamber mixture ratio	5 – 7	2.8 – 3.8	2.6 – 3.3
Preburner mixture ratio	0.5 – 0.67	0.2 – 0.4	50 – 56
Preburner gas temperature	650 K – 750 K	650 K – 750 K	650 K – 800 K

Table 2: Functional domains realized with the European staged combustion pathfinder.

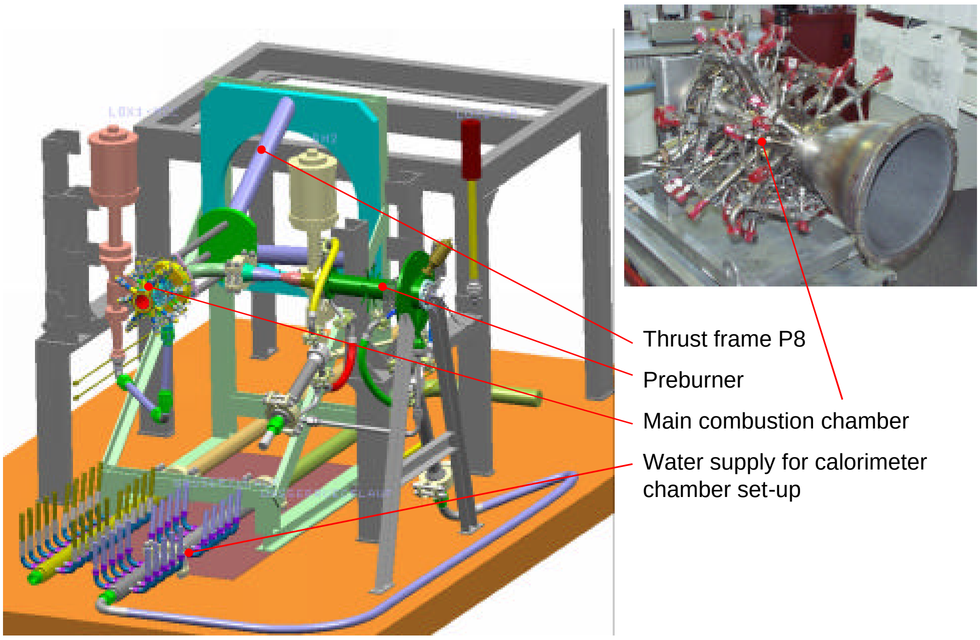

Figure 6: Staged combustion pathfinder, with preburner and calorimeter main chamber set-up (top right).[5]

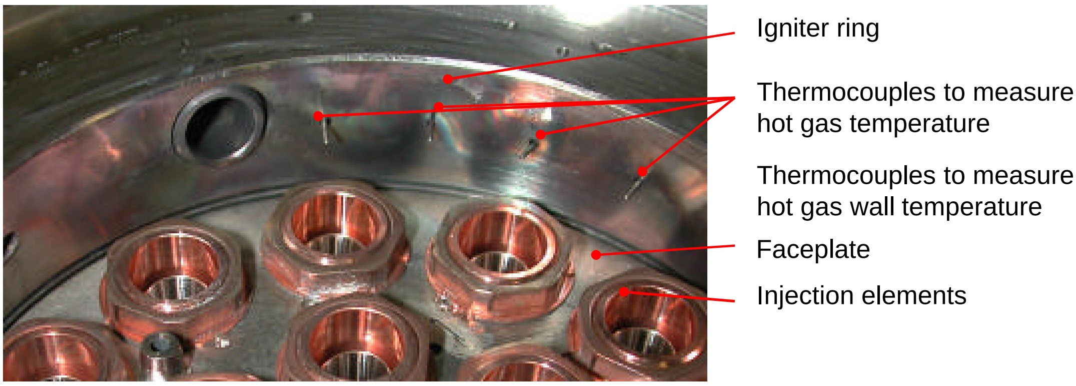

Figure 7: Measurements foreseen for staged combustion injector faceplate.

The main combustion chamber injector head design orientates from the hot gas routing aspect at the LOX/Hydrogen reference engine design. Here, two basically different approaches were benchmarked, with the preburned gases feeding through the sides (as realised with the SSME main chamber injector head), or from the top (as realised with the RD-0120 main chamber injector head). Table 3 summarises some aspects considered for the trade-off. Favour

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[3] Not part of FLPP, but information exchange foreseen with complementary German / Russian technology programme TEHORA. [7]
[4] Limited by hardware constraints.
[5] Ablative nozzle extension mounted for demonstration purpose only; not considered within FLPP objectives.

was given for the preburned hot gas feeding from the top, allowing for a very compact injector head design. This conclusion reflected also the problems encountered with the SSME, see e.g. Ref. [8].

	Hot gas routing from side, central feeding for LOX	Central hot gas routing, with LOX from side
Example	SSME	RD-0120
TP mounting issue	Compact to sides, with integrated hot has manifold (see SSME)	Compact design possible
Overall dimension , incl. manifolds	Large hot gas manifold needed, (risk of LOX-post vibration and failure as observed at SSME)	Compact manifold design possible
Thermo-mechanical load situation	- (considered as disadvantage)	+ (considered as advantage)

Table 3: Propellant routing options for staged combustion main chamber.

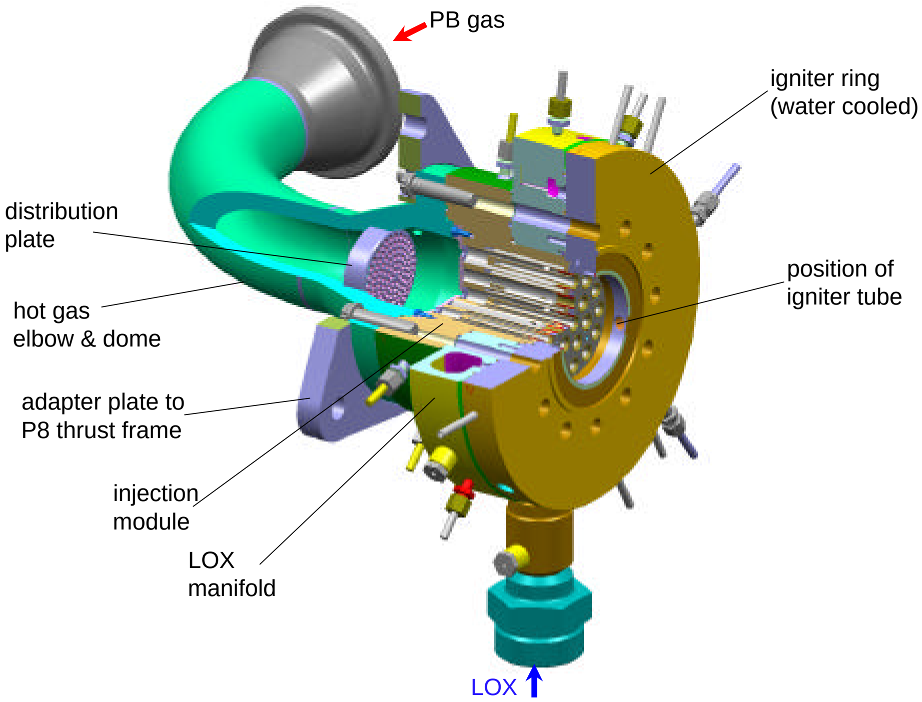

Figure 8: Main combustion chamber injector head for 55 kN staged combustion demonstrator.

The LOX/Hydrogen reference engine employs a GH_2-cooled faceplate design. For the staged combustion demonstrator, also here various options were benchmarked, including an un-cooled faceplate, a transpiration cooled faceplate, a LOX-cooled faceplate, a GH2-cooled faceplate, and a water cooled faceplate. It was concluded specially with focus on the calorimeter heat flux measurements as central test objective for the staged combustion demonstrator, to include a water-cooled faceplate into the design. The faceplate will be strongly instrumented to characterise the gas temperatures at and near the faceplate and to quantify the hot gas side heat transfer. Figure 7 illustrates some details on measurements and principle injector face plate layout. It is noted that the picture shows a faceplate for a gas generator engine cycle. Figure 8 sketches the integrated injector head design, with hot gas feeding from the top, and LOX-feeding from the side.

Due to the dual-use for both propellant combinations Hydrogen and Methane, only the fuel-rich LOX/Methane aspects can be addressed through the demonstrator design.

The test programme for both propellant combinations will be conducted in 2007 and 2008 on the DLR test facility P8 at Lampoldshausen. DLR will contribute to this test programme as test service provider. It is further planned to include a high pressure regenerative nozzle extension hardware into the demonstrator test objectives, manufactured by Volvo Aero with their sandwich technology.[9] Also here, dual-use of the hardware regarding coolant fluids (Hydrogen and Methane) is foreseen.

5. Conclusion

Within the Future Launcher Preparatory Programme FLPP, a requirement driven development approach has been selected to define the propulsion system requirements and to derive the need for further technology demonstration by ground tests. On engine system level, three reference engine concepts have been worked out by the propulsion consortium, one for each fuel combination LOX/Hydrogen, LOX/Methane and LOX/Kerosene. The staged combustion engine cycle concept has been adopted for all three reference engine cycles. For each propellant combination LOX/Hydrogen, LOX/Methane and LOX/Kerosene, various staged combustion cycles were analysed and benchmarked. The reference cycles have been finally selected based on a cost-benefit analysis.

Technology work started on identified critical subsystems, including turbopumps, valves, and staged combustion devices. The technology demonstration by specific component ground tests clearly aims at a successful demonstration of TRL > 5 by 2010, and addresses long-life and high performance technologies. Dual-use technologies for different propellant types are considered throughout the programme. As example, the 55 kN thrust chamber and preburner for the staged combustion demonstration has been analysed for Hydrogen and Methane, incorporating a minimum amount of hardware changes by switching the propellant type.

It is planned in the forthcoming step that subcomponents and components - after their successful individual demonstration - will be designed, built and integrated into an engine demonstrator. Thrust level and thus engine scale, propellant type and cycle layout remains to be defined within the near future, enabling a successful demonstration of scale-dependent objectives on engine system level.

To conclude, the ESA Future Launcher Preparatory Programme is successfully integrated within the European space community. Commitments are given by all partners to succeed with the overall programme objectives, thereby shaping Europe’s future in the evolution of its cost-efficient and highly reliable space transportation systems, and safeguarding the independent European access to space for the years to come.

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