Technology Development Program for a New Storable Propellant Low-Thrust Engine Demonstrator

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Abstract
FLPP Storable is a technology demonstration project with the main objective of readying the technologies for a development application for a pressure fed, low-thrust upper stage engine with a thrust level of 5 kN and a chamber pressure of 15 bar. Applied technologies have to show full scalability within a thrust range of 3…8 kN. The final goal of the FLPP Storable Propulsion Demonstration Project is the successful hot-firing demonstration of the full-scale demonstrator hardware at a technology readiness level of 5-6. This paper describes a detailed analysis of existing relevant technologies as candidates for the demonstrator engine. Based on this overview, a characterization of these technologies shows the level of technical readiness for a possible application in the proposed storable engine demonstrator. After the identification of individual technical readiness levels, concepts are derived to investigate the potential of increasing the technology readiness level, if necessary, to meet the requirements of the technical demonstrator engine.

1. Introduction

Astrium Space Transportation, abbreviated Astrium ST, is Europe's leading manufacturer of propulsion systems for launch vehicles, satellites and in-orbit propulsion systems. Due to the specific needs and requirements for European space missions, Astrium ST has developed a solid and broad technology basis for storable propellant engines in the past, starting in the early 1970s. The Astrium ST portfolio on storable engines includes satellite attitude and reaction control systems, spacecraft attitude control systems and liquid apogee engines, and upper stage space launcher engines. The thrust of these storable propellant engines lies between a few Newton for mono-propellant and bi-propellant satellite attitude and reaction control systems up to 30 kN for the pressure-fed bi-propellant Aestus upper stage engine. Aestus is currently in use for European ATV missions after a successful implementation of re-ignition capability could be demonstrated in 2007 with more than 150 re-ignitions under representative operating conditions. Another important step forward in the field of storable engine technology was the development and testing of the pump-fed high-pressure Aestus II/RS-72 Pathfinder Demonstrator during a joint venture with PW-Rocketdyne in the late 1990s.

Due to the excellent storage behaviour in combination with a high specific impulse storable propellants are widely used for upper stage engines up to a medium-thrust range. Furthermore, long-duration missions and deep-space missions with in-orbit storage times up to months and years rely on storable propellants as well as space exploration missions. Propellant combinations like MMH (monomethylhydrazine) as fuel and NTO (nitrogentetroxide) as the oxidizer are the optimum solution for a broad variety of missions and application scenarios which are in the current focus of the European Space Agency (ESA) and the German Space Administration (DLR). VEGA evolution with a European upper stage module, Next Generation Launcher (NGL) for kick-stage applications, and Moon and Mars missions like Moon Lander (Next) and Mars Sample Return (MSR) are of specific interest [1].

Figure 1 depicts a summary of Astrium ST storable engines, arranged at their specific thrust and specific impulse levels. Furthermore, the development needs for a storable bi-propellant engine in the thrust class between the upper stage engine Aestus and 400 N thrusters can be seen in this figure. For the moment this mid-thrust range is not covered in the Astrium ST company portfolio and is the aim of the herewith described currently running technology development program.

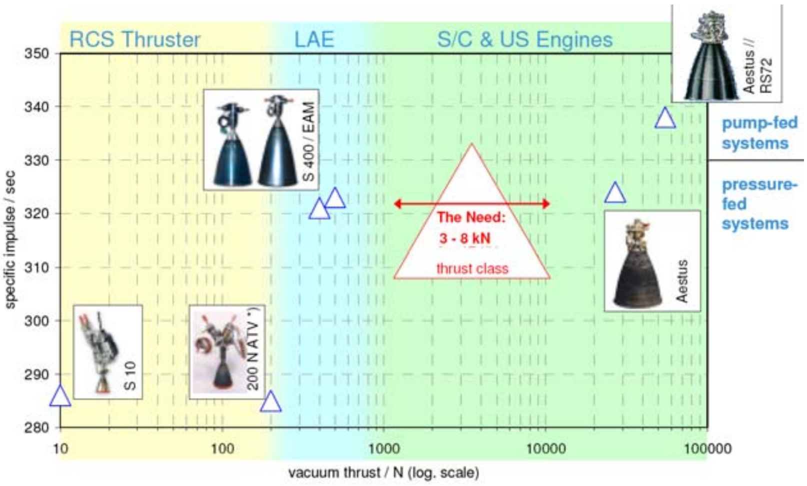

Figure 1: ASTRIUM storable engine portfolio

2. FLPP Storable Propulsion Demonstration Project

FLPP Storable is an ESA-funded technology maturation program within Europe's Future Launcher Preparatory Program, which started in April 2010 with the kick-off of Set 1. Main objectives of the FLPP Storable Propulsion Demonstration Project are identification and demonstration of critical technology items for low- and mid-thrust bi-propellant storable engines for future European mission applications. The herewith described Future Launcher Preparatory Program for Storable Engines directly aims for a technology demonstration of a 5 kN engine demonstrator. However, the investigated and developed technology items within FLPP Storable shall be applicable and scaleable for a thrust range of 3…8 kN. This guarantees a maximum of technology outcome for FLPP Storable as well as a broad applicability for future ESA mission requirements and scenarios while keeping the development and testing efforts and costs at a lower level compared to an engine with a higher thrust. The FLPP Storable Propulsion Demonstration Project is in close coordination in terms of concept study with the national-funded VEGA New Upper Stage Program (VENUS II) which focuses on a Europeanization of the VEGA launcher with a replacement of the currently featured AVUM upper stage engine and an improvement of the current VEGA launcher performance [2].

Main challenges of FLPP Storable are the heat management of the combustion chamber including regenerative cooling demonstration featuring MMH and NTO, injector performance, and combustion stability. The overall development logic, based on Astrium ST Aestus and Aestus II heritage, is shown in the following Figure 2. After identifying critical technologies, laboratory-scale tests, e.g. for investigation of NTO regenerative cooling, as well as subscale tests for injector selection and performance and stability verification will be done in combination with analytical support and CFD enhancement and validation. The final step will be the full-scale demonstration and verification of the FLPP Storable demonstrator hardware.

Figure 2: Overall development logic for FLPP Storable

3. FLPP Storable Demonstrator Engine Requirements

A main scope for the development of the FLPP Storable engine demonstrator lies in the development of a highly efficient injector design which will also guarantee stable combustion behaviour. Furthermore, investigations for regenerative cooling with NTO in addition to MMH regenerative cooling are one of the major technology development needs. Up to now no Astrium ST heritage can be used for NTO regenerative cooling development. With a decreasing thrust level in combination with high specific impulse requirements, the relative heat load for the coolant in the cooling channels of a regenerative cooling system increases and the risk of MMH decomposition and vaporization occurs. Studies have shown that in the requested thrust range the cooling duties have to be divided between MMH and NTO in order to guarantee sufficient thermal margins not only at the reference point but also for a design and operational envelope. For the development and design of a MMH regeneratively cooled system, Astrium ST can revert to Aestus and Aestus II experiences. NTO regenerative cooling, on the other hand, is identified as a key technology to be developed within FLPP Storable. The FLPP Storable demonstrator will also feature MMH film cooling, however only for film cooling verification and code enhancement reasons. The demonstrator shall be able to run safe and stable at all envelope points without the injection of an additional MMH film favouring overall engine performance. In general, specific requirements on engine level can be summarized as follows:

- Engine thrust level in the range of 3…8 kN to meet ESA mission requirements
- Reach a TRL of 5-6 for individual technologies involved in the technology program
- Pressure-fed engine system with a combustion chamber pressure high enough for sufficient performance but limited to respect the stage pressure budget
- High combustion efficiency and robust cooling design in combination with low combustion roughness
- Engine cooling needs to be efficient due to long-duration mission and high-performance requirements; film cooling will only be included for demonstration objectives
- Safe and stable re-ignition behaviour with limited sensitivity to propellant inlet temperatures
- Sufficient margins against HF

Table 1 summarizes reference conditions and requirements for the 5 kN FLPP Storable demonstrator engine.

Table 1: FLPP Storable demonstrator engine reference conditions and requirements

FLPP Storable demonstrator engine	
Propellants	MMH (fuel) / NTO (oxidizer)
Combustion chamber pressure	P_c = 15 bar at the reference point
Thrust level	F = 5 kN
Specific impulse	> 320 s at vacuum condition
Mixture ratio	O/F = 2,0 at the reference point
Re-start capability	Up to 13 times
Total burn time	5000 s
Maximum single burn time	2500 s (not to be demonstrated on test bench)

Compared to the chamber pressure of 11 bar for the bi-propellant upper stage Aestus engine, 15 bar was chosen for FLPP Storable. Main advantages of an increased chamber pressure are tendency towards higher combustion efficiency as well as increased stability margins, reduced engine mass due to reduced engine size, and increased specific impulse while the impact of the higher combustion chamber pressure has no significant impacts on cooling margins of the engine demonstrator and is still acceptable from stage pressure budget point of view. Increased injection element loading was found not being detrimental from Aestus II demonstrator engine and VENUS II technology testing.

Major system and technology components of the FLPP Storable demonstrator are:

- Injector head, domes for MMH and NTO, face plate, injection elements, and fuel and oxidizer manifolds
- HF damping devices like acoustic baffles and quarter-wave resonators
- Combustion chamber, including the cylindrical part and a convergent-divergent part with the throat section
- Cooling system, which includes NTO and MMH regenerative cooling as well as optional MMH film cooling features
- Radiation cooled nozzle extension
- Propellant valves (oxidizer and fuel main valve including a purge unit)
- Feed lines (oxidizer and fuel lines, purge lines)
- Instrumentation

The main objectives of the FLPP Storable Propulsion Demonstration Project can be summarized as follows and give an overview of customer needs and mission requirements. All full-scale tests with capacitively and regeneratively cooled hardware will be performed at the P2 test bench in Lampoldshausen:

- Demonstration of NTO regenerative cooling and static combustion stability: NTO regenerative cooling shall be designed with sufficient margins for all load points, and the engine shall be able to demonstrate static stability within the feasible test scope without any HF damping device. The demonstrator hardware shall arrive at stable steady-state conditions after priming and ignition processes.
- Demonstration of steady-state performance parameters: This includes the desired combustion efficiency at low combustion chamber roughness comparable to Aestus and Aestus II.
- Demonstration of MMH film cooling: The cooling design of the engine shall be robust and bear sufficient margins for all load points without the application of a film. Film cooling acts like additional risk mitigation and shall demonstrate engine growth capabilities for lower thrust applications.

- Demonstration of temperature sensitivity: The engine shall be able to operate safely with heated and unheated propellants, like also demonstrated on Aestus.
- Demonstration of HF damping devices: Stability against artificial disturbances (bomb test) shall be demonstrated with a tuneable absorber concept and an uncooled baffle design.

3.1. Injector Head

A variety of injector concepts for storable propellant engines featuring high specific impulse requirements has been developed at Astrium ST in the past:

- Double-swirl injector which is mainly used in small thrusters and apogee engines
- Combined swirl-jet concept as applied in Aestus and Aestus II designs
- Derivatives of the double-swirl and swirl-jet concepts

Based on VENUS II pre-characterization these three element types will be investigated during cold-flow and hot-run test campaigns within FLPP storable. After the hot-firing single-element campaign, a decision towards a baseline element and a back-up element will be done based on the test results. These elements will then be investigated with a full-scale injector head to demonstrate the element design capabilities on multi-element level. Figure 3 depicts the injection technology development logic for FLPP Storable, divided into sub-scale (Set 1) and full-scale (Set 2 and further sets) investigations.

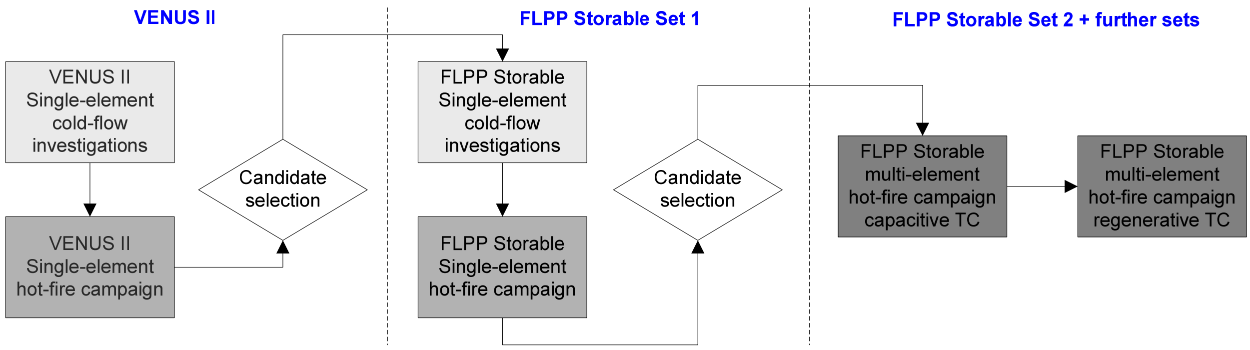

Figure 3: Injection technology development logic

Single-element hot-run experiences based on VENUS II test results are used to choose a proper element design for FLPP Storable. A further improvement of one or two of the most promising element types investigated within VENUS II will be conducted within FLPP, also in the frame of single-element hot-firing tests. A major scope of the single-element test is the investigation and comparison of technology items like combustion efficiency, combustion roughness, and spray characterization by high-speed video recordings. Building on the experience gained from the Venus II single element characterisation, three evolved element types have been defined for FLPP Storable:

- Variant A: Aestus-scaled element with radial slots on the fuel side and a swirl insert on the oxidiser side. The fuel side contains rows of small diameter orifices upstream of the slots acting as filter to protect the slots against particle contamination. The number of these orifices is tuned to meet the pressure drop specifications based on Venus II experience.
- Variant B: Aestus-scaled with inclined radial slots on the fuel side and a swirl insert on the oxidiser side. This variant features the same geometry as Variant A, only the slots are inclined by 45°.
- Variant C: Double swirl element. The swirl on both propellant sides is generated by means of tangential orifices. Optimisation of the element design to improve combustion roughness and optimise the combustion efficiency, based on Venus II experience.

3.2. Cooling Technique and Engine Architecture

In the following an overview of the cooling concept and technologies approved to the demonstrator is given accomplishing the requirements in terms of high performance and long-time engine duration:

- MMH regenerative cooling (convective cooling) of the liner is a typical well-proven cooling technique for storable propellant engines featuring high performance. Astrium ST has an extensive heritage on the development of MMH regenerative cooling systems due to the Aestus and Aestus II engines.
- The application of NTO regenerative cooling is a new technology for Astrium ST but was found necessary as an additional cooling means to ensure proper engine cooling margins. Besides analytical investigations on heat transfer within FLPP Storable, NTO cooling investigations will start with the development of a single-channel hardware which can be heated by electrical heaters. This technology was successfully used for hydrogen and methane using straight and curved cooling channels at DLR Lampoldshausen. The single-channel experiment will allow controlled conditions for heat load, mass flow rate, and pressure losses. To validate the experiment and the connected numerical tools, water will be used for first test and model validations. After the validation of the numerical tools NTO will be applied and heated by the electrical heaters while flowing through the cooling channel. Thermocouples arranged at the channel wall will detect the local wall temperature and will allow for calculating the local heat flux densities. Using the measurement data a verification and validation of numerical tools will be possible. The code validation is necessary for designing the NTO regenerative cooling system of the full-scale demonstrator.
- Accompanying with the single-channel NTO cooling experiment fluid property data validation will be conducted. Sound fluid properties are the key element for designing and simulating a proper regenerative cooling system with respect to the complex composition of NTO, which is an equilibrium mixture of N_2O_4 and NO_2, depending on pressure and temperature.
- In order to account for incompatibilities of NTO with typical nickel materials, the cylindrical cooled combustion chamber section will be made of steel with wire-eroded cooling channels.
- The FLPP Storable demonstrator will also investigate capabilities and associated effects of film cooling with MMH. MMH film cooling is mainly used for small-thrust engines. Astrium ST has heritage in developing film cooled thrusters with a thrust level up to 500 N. Engines with higher thrust like Aestus or Aestus II do not feature film cooling for performance reasons.

A detailed trade-off regarding the cooling architecture of the demonstrator hardware has been done, supported by extensive numerical analyses of all options. The final cooling concept selected as best compromise among several candidates is shown in Figure 4.

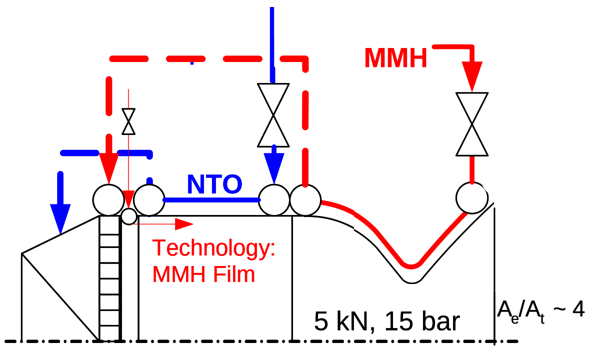

Figure 4: FLPP Storable cooling architecture

The selected design features maximum modular flexibility. The cylindrical part will be regeneratively cooled by NTO while the thermally higher loaded nozzle throat segment will be cooled regeneratively with MMH. Between the injector head, a film injection segment can be placed for film cooling investigations. The MMH film will be controlled by a separate feed line system and is independent from the injector head mass flow. To guarantee full-flow conditions at all load points, the lowest chamber-pressure envelope point was taken into account to derive the maximum possible expansion ratio.

For a safe design a pressure ratio at the end of the nozzle throat segment of $p_{wall}/p_{ambient} = 0.4$ was chosen as the driving criterion for the choice of the maximum possible expansion ratio. This analysis results in an allowable expansion ratio of $\varepsilon = 4.0$.

Cooling analysis predicts bulk temperatures for MMH and NTO regeneratively cooled sections to be well below the boiling temperatures of the fluids. However sub-cooled nucleate boiling is expected locally for MMH and NTO parts, which favours the local heat transfer and increases the cooling capability.

Figure 5 shows the layout of the demonstrator engine with an expansion ratio of $\varepsilon = 4.0$ in the MMH-regeneratively cooled part. In a later set, a radiation cooled nozzle extension will be adapted. A variety of measurement technique - thermocouples and pressure transducers - will guarantee the fulfilment of demonstration objectives and allow a safe operation of the hardware.

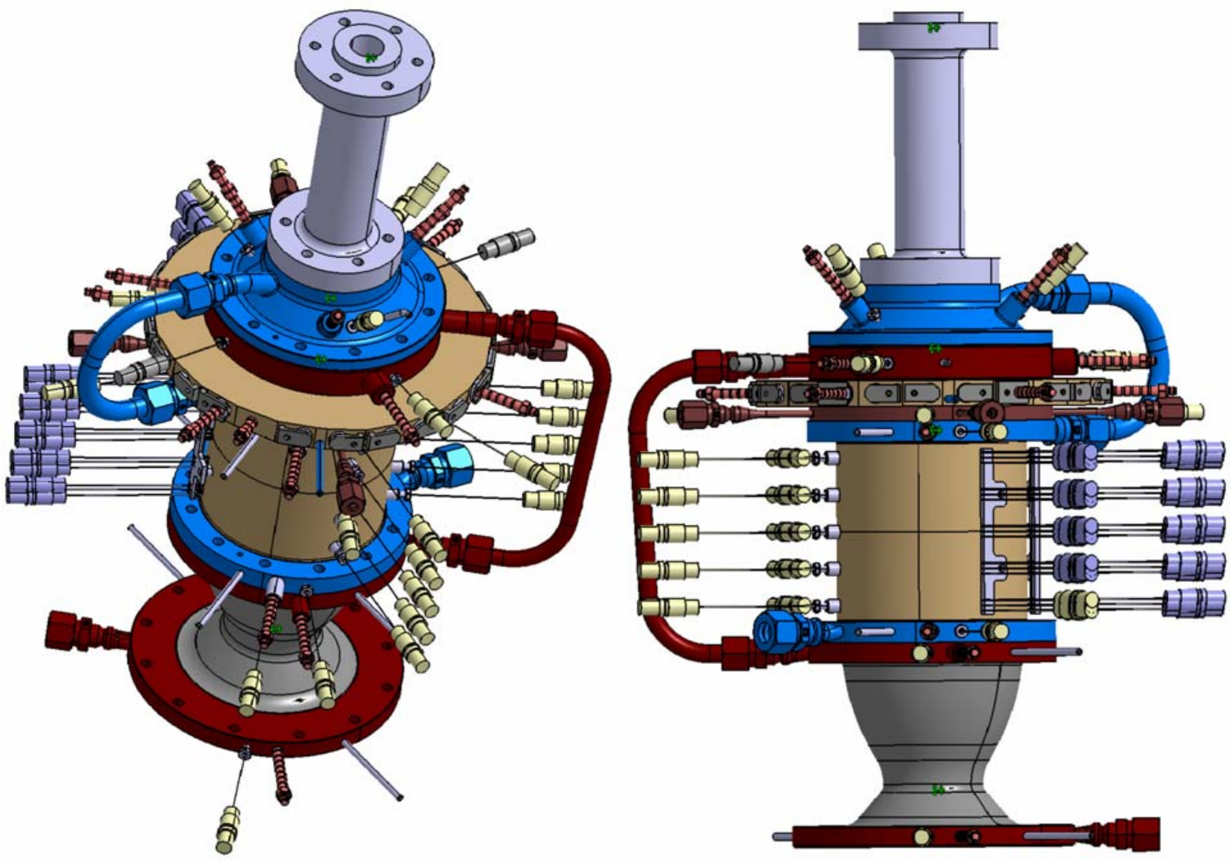

Figure 5: FLPP Storable engine demonstrator layout

3.3. NTO Regenerative Cooling Technology

As mentioned already, NTO regenerative cooling is a key technology within FLPP Storable. Lab-scale tests will prepare the technology readiness for the final application in the demonstrator. Within FLPP Storable Set 1, NTO-cooling investigations will start with the design of an electrically heated single cooling channel (EHT). This test campaign will be performed at the P1.0 in Lampoldshausen in cooperation with DLR. In parallel to the electrically heated channel design a sensitivity analyses has been performed to investigate NTO cooling margins in terms of vaporization and boiling. Based on this analysis, a demonstrator hardware conceptual design has been done. After analyzing the electrically heated channel results a verification of the regeneratively cooled demonstrator concept will conclude Set 1 activities. The main test objectives of the EHT test campaign can be summarized:

- Investigation of heat transfer behavior of NTO flowing through a representative cooling channel section
- Investigation of real-engine-like heat flux conditions
- Investigations of different materials (Ni, steel) in combination with hot NTO
- Investigations of heat transfer margins like bubble boiling

The design of the electrically heated channel will feature an interchangeable cooling section in the middle of the test specimen, and two outer half-shells with 12 electric heating elements. The material for the outer shells and the cooling channel section will feature high thermal conductivity (aluminum, copper). High-precision machining will ensure maximum heat conductivity from the heated outer shell parts to the inner cooling channel section. The shell-design allows for changing the inner section which contains the cooling channel. Rectangular or round cross sections can easily be applied for the cooling channel design to provide maximum experimentally flexibility. The shell-design allows also for high-precision positioning of thermocouples in the channel section to measure the thermal gradient of the cooling channel section wall.

Figure 6 shows the EHT setup. On the left one shell and the gold-plated cooling channel section is visible. The gold-plating shall increase the thermal conductivity between the outer copper shells and the inner cooling channel section. On the right the final setup including measurement technique is depicted. The test campaign is planned for June/July 2011 at the P1.0 test bench in Lampoldshausen.

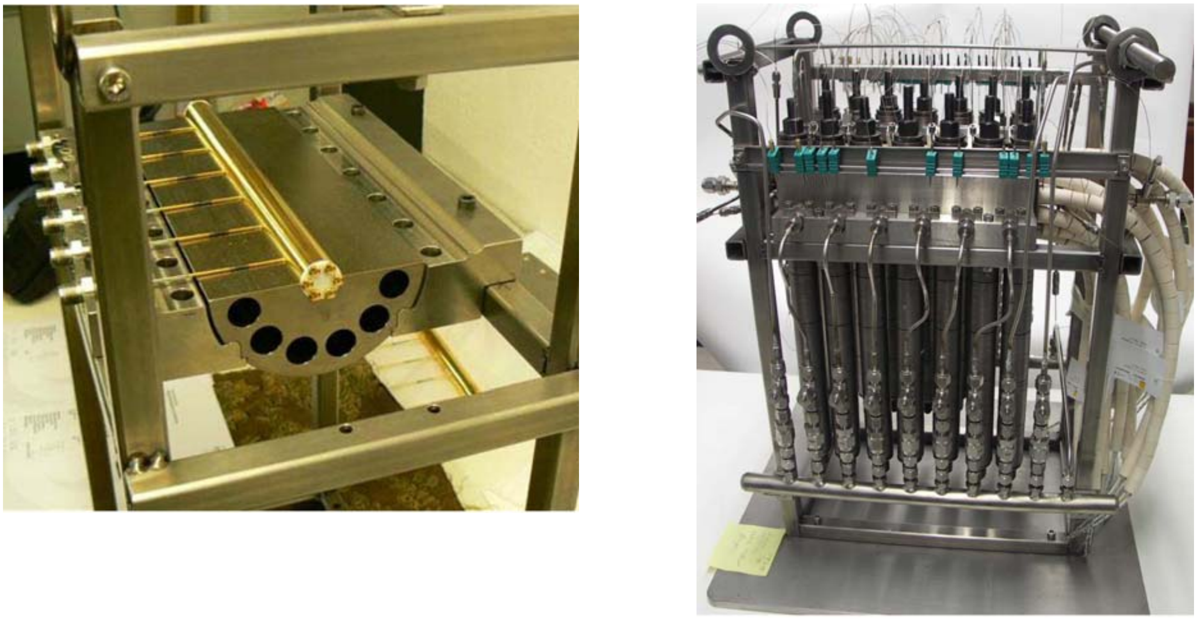

Figure 6: EHT modular setup with gold-plated nickel tube (left); side view of mounted setup (right); (photographs published with permission from DLR Lampoldshausen)

The main components of the EHT setup are as follows:

- Two outer copper shells with electrical heaters to provide the desired heat load
- A removable cooling-channel section which will be mounted between the two outer copper shells. NTO will flow through a rectangular 2 mm x 2 mm cooling channel, which features a length of 250 mm; the concept allows for an easy change of the channel section and the investigation of different channel materials
- A spring system which compensates thermal expansion and contraction of the different parts of the setup; the spring system features a defined force to ensure a stable contact between the outer and inner parts, which is important for the heat conduction from the electrical heaters to the NTO flowing in the cooling channel
- A flow-inlet section with flow straightener to guarantee best possible flow conditions and minimized turbulences at the inlet of the cooling channel section
- A flow outlet section which minimizes flow turbulences at the outlet of the cooling channel section
- Measurement technique in terms of thermocouples and pressure transducers, located at the inlet position, the cooling channel section, and the outlet position
- Test-bench connected measurement technique to control mass flow and to monitor NTO conditions at the EHT inlet and outlet positions

3.4. HF Damping Devices

A crucial part of the injector head design is the HF damping device. Damping devices are necessary to enlarge combustion stability margins. Table 2 gives an overview about typical types of combustion chamber instabilities.

Table 2: Types of combustion chamber instabilities

Description	Frequency (Hz)	Remark / Relationship
Low frequency (LF); (chugging)	10-400	Interaction of propellant feed system (or entire vehicle) with combustion chamber
Intermediate frequency; (buzzing)	400-1000	Linked with mechanical vibrations of propulsion structure, injector manifold, O/F variations, and propellant feed system resonances
High frequency (HF); (screaming, screeching)	> 1000	Linked with combustion process forces and chamber acoustical resonance properties

Especially high frequency (HF) phenomena have to be addressed to guarantee a stable operation of the FLPP Storable demonstrator. Energy content increases with frequency, and so HF is most destructive and capable of destroying a combustion chamber in much less than a single second.

Damping devices can help to increase the stability margin of a combustion chamber and overall engine system. However, as a design rule, the engine has to be fully operational without any absorber concept. This will be demonstrated with the capacitive cooled hardware, where the damping concepts will be removed during the test campaign. However, the HF damping devices like absorber or baffles shall give additional stability margins in case of artificial (e.g. bombs) or unintentional disturbances. Typical HF damping devices are [4,5]:

- Helmholtz resonator: Cavities which are designed as Helmholtz resonators – a cavity in the chamber or injector head wall with a small passage entry – feature a relatively high absorption bandwidth. The resonance frequency can be calculated as a function of the local acoustic velocity, cavity and passage entry dimensions. Helmholtz resonators consist of a comparable thin duct connected to a large backing volume of larger diameter.
- Quarter-wave resonator ($\lambda/4$ resonator): Quarter-wave resonators feature very high absorption efficiency at a very small acting bandwidth (discrete frequency). Due to this design feature quarter-wave resonators are sensitive to temperature and chemistry (mixture ratio, combustion products). These cavities consist of a duct of constant cross section whose diameter is small compared to its length. The length of the duct is chosen in such a way that the principal longitudinal eigenfrequency corresponds to the frequency to be damped in the chamber. Tangential or radial eigenmodes in the cavity are unlikely to appear due to the small diameter. A special way to design and integrate quarter-wave resonators is the undercut design. In this design, the cavities are not located directly at the wall of the combustion chamber, but in an undercut groove, at the diameter of the face-plate which leads to a location behind the level of the face plate and at the diameter of the chamber. In general, this configuration can be used with different kinds of absorbers. Advantages of this configuration are the undisturbed chamber wall, which still permits the application of film cooling. Furthermore, the orifices are located outside the spray zone, which prevents contamination with propellants, and gives also an improved thermal resistance against the hot combustion gases. The undercut design was already applied in the Astrium ST DB50 design, which was successfully tested in 1995.
- Injector baffles: Baffle design is based on the assumption that severe instabilities are located in or near the atomization zone close to the face plate. Therewith, baffles result in a de-coupling of gas dynamic forces with the combustion chamber. Baffles have to resist thermal and mechanical loads due to their protrusions into the combustion chamber. Adequate cooling of the baffles can be necessary, depending on baffle height and engine operating condition.
- Pocket absorbers as used in the Space Shuttle OMS engine: This configuration provides a comparable large aperture area. However, the acoustic properties of these effectively two-dimensional cavities are not sufficiently known and understood. The incorporation of a possibility to tune this kind of absorber to different frequencies of the test bench is considered more difficult than for conventional $\lambda/4$ cavities. Additionally, conventional cavities with circular orifices provide more edge-length per aperture area, and, hence, potentially higher damping since turbulent phenomena and associated floe energy dissipation at the edges are an important loss mechanism. The TRL at Astrium ST is lower than 2 which impedes the use of this concept for the present study.

Due to the above shown TRL determination and technology assessment, two different HF damping device concepts will be investigated within FLPP Storable, tunable quarter-wave resonators and uncooled mechanical baffles. Figure 7 depicts the preliminary logic for verifying the HF damping device capability. As a design rule – comparable to MMH film cooling technology within the overall cooling duty – the demonstrator hardware has to show stable and safe operation without any HF damping device technology.

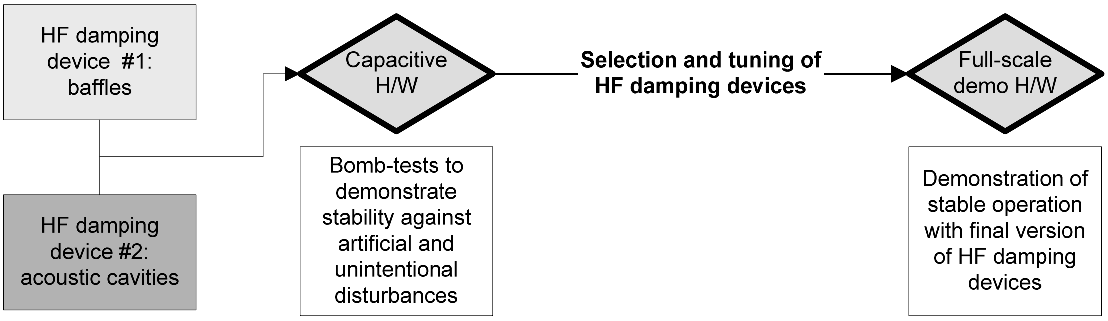

Figure 7: HF damping device development logic

The HF damping devices will give additional stability margins for the demonstrator hardware during transient and stationary operation and will act against unintentional disturbances. Bomb-tests with the capacitive hardware will show the stability against HF disturbances with and without any HF damping devices. The damping devices will be developed in a way that allows for implementation, removal, and tuning during the test campaign with the capacitive hardware. After a successful demonstration of the capacitive hardware without any damping devices, the demonstration of the final damping concept will be done with the FLPP Storable demonstrator hardware.

4. FLPP Storable Test Logic

The general test logic of FLPP Storable is depicted in Figure 8. Subscale testing is restricted to hot-firing of the three initial injector concepts at the P2 in Lampoldshausen, while the transition to full-scale investigations start with the selection of the two most promising element concepts to be tested further within FLPP Storable.

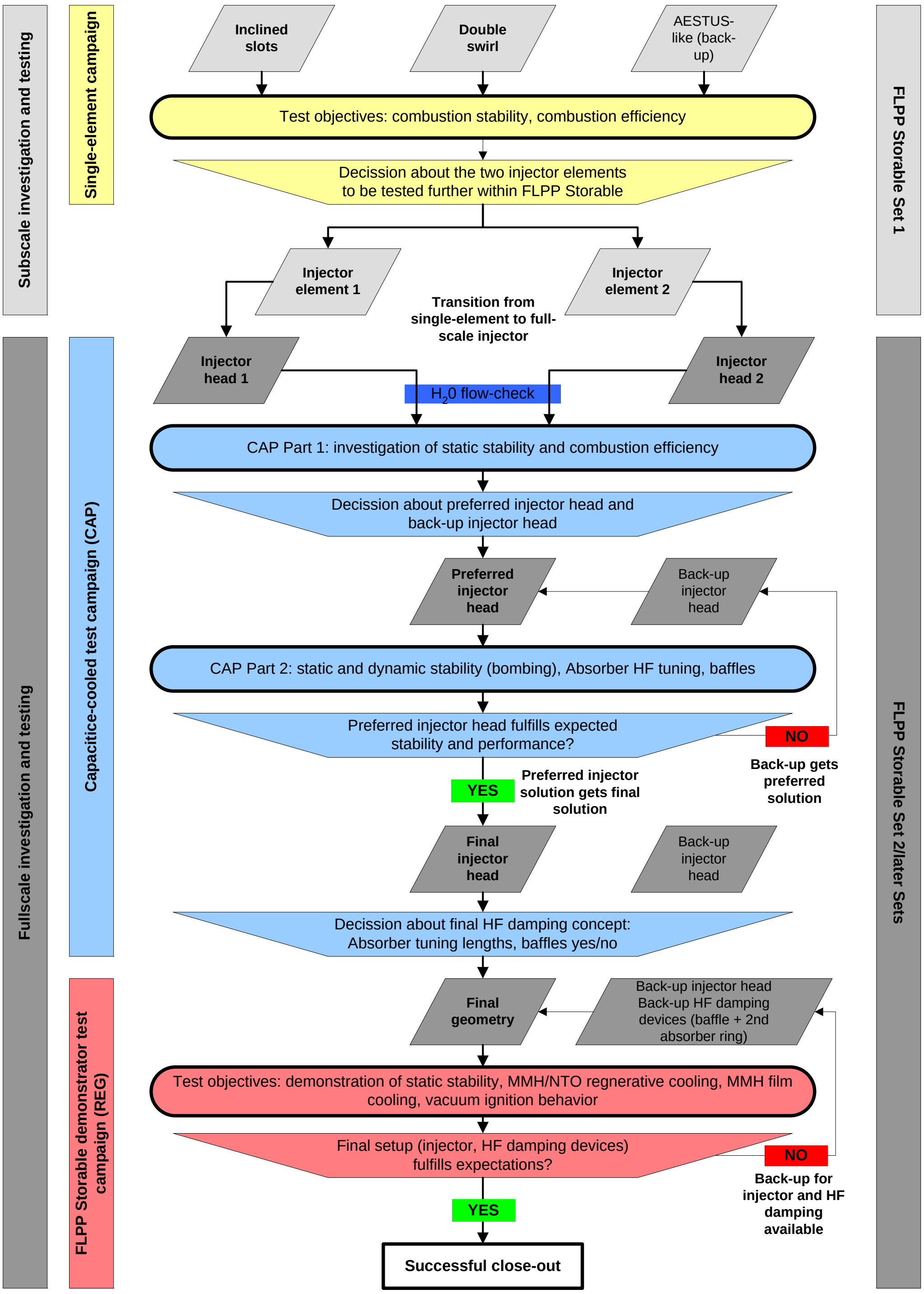

Figure 8: Overall FLPP Storable test logic

Full-scale test campaigns are divided into two major parts on the P2, investigations with a capacitive chamber, and final demonstration with a fully regeneratively cooled hardware. Objectives of the capacitive hardware investigations are static stability and combustion efficiency of the full-scale injector head as well as bomb tests and absorber tuning for static and dynamic stability investigations. The final regeneratively cooled hardware will aim at the demonstration of major FLPP Storable objectives like MMH and NTO regenerative cooling mastering, film cooling, and vacuum ignition behavior. In addition, transient start-up and shut-down behavior together with sequence investigations will be addressed.

5. Summary and Outlook

European space mission analyses showed the demand for a highly-efficient storable bi-propellant engine in the thrust class 3…8 kN which is currently not covered by the Astrium ST portfolio. This paper gives an overview of the FLPP 2.2 Storable Program which aims at preparing critical technologies for a future engine design in the required thrust class. Injection technologies as well as engine cooling technologies are in the scope of the FLPP Storable Propulsion Demonstration Project. The demonstration of NTO regenerative cooling in combination with a high specific impulse and high combustion stability underlines the ambitious character of this technology program. Furthermore, film cooling will be included in the final design as a demonstration objective. Within the currently running Set 1 of activities a representative demonstrator engine is specified and designed based on a well-consolidated set of requirements, while the upcoming Set 2 aims at manufacturing and full-scale testing activities. At completion of the herein described FLPP Storable Propulsion Demonstration Project, the challenging technologies addressed and described in this paper will have reached a TRL of 5-6. This will be a robust and valuable basis to enter a potential engine development program at low cost and reduced schedule.

Acknowledgements

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