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FLPP ETID: TRL6 reached for Enabling Technologies for Future European Upper Stage Engines

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Abstract

Within ESA-Launchers, the Future Launchers Preparatory Programme (FLPP) Expander Technology Integrated Demonstrator (ETID) project focusses on the full-scale demonstration of cost-effective and low-weight expander liquid rocket engine technologies. The overall goal is to reach TRL 5-6 for the chosen technologies by hot-fire testing in fullscale at P3.2 in Lampoldshausen, Germany. The paper will present the outcomes of the hot-fire test campaign conducted between June 2018 and March 2019. A total of 23 hot fire test days have been performed on 4 different hardware configurations. A cumulated runtime of 2707sec distributed across more than 40 operating points has been achieved on the test articles. The demonstrator hardware consists of a thrust chamber assembly (TCA) and three different electro-driven rocket engine valve types.

1. Introduction

This paper is meant to give a project overview of the FLPP ETID programme with respect to the overall development logic and project status. The different products which are investigated inside the programme will be introduced. Focus is laid on the enabling technologies which have been selected for maturation through hot-fire tests at P3.2.

2. Project Overview

2.1 Industrial Setup

The industrial setup of FLPP ETID project is presented in Fig. 1. The prime contractor is ArianeGroup GmbH (AGG) located in Ottobrunn/Taufkirchen, Germany. The AGG's scope of work encompasses the engine system level activities, the TCA related work packages and the design and manufacturing of electrical driven engine valves. GKN Aerospace AB, Trollhättan, Sweden, is providing the nozzle extension. Safran Aero Boosters, Liège, Belgium, is developing electrical driven engine valves that will be employed in the test configurations. Two different innovative ignition systems are investigated by the Carinthian Tech Research (CTR), Villach, Austria, and Aerospace Propulsion Products BV (APP), Klundert, The Netherlands, respectively. The company NAMMO in Dublin, Ireland

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is investigating the usage of Aluminium for the engine lines. The Czech Technical University (CTU), Prague, has been developing statistical approaches to be used for combustion chamber liner life computation and health monitoring concepts for rocket engines. The hot fire test campaign is performed at P3.2 test bench of Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Lampoldshausen, Germany.

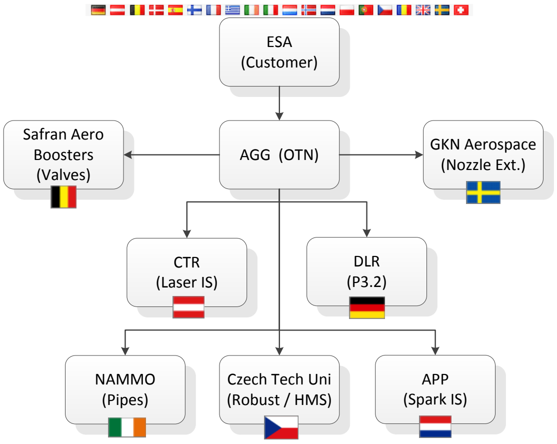

Figure 1: Industrial Setup

2.2 Schedule

Phase 1 of the ETID project was kicked off in July 2013 covering the development of the demonstrator up to its Preliminary Design Keypoint (PDKP) and the subsystems e.g. nozzle extension (NE), thrust chamber assembly (TCA), regulation valve (RGV) up to the respective Manufacturing Readiness Keypoints (MRKP). In order to expedite the overall project schedule the design loops on demonstrator level and subsystem level were performed in a concurrent way (see Fig. 2).
With the PDKP of the demonstrator the last main milestone of Phase 1 was performed in December 2015. Phase 2 that covers the manufacturing, the hot fire test-campaign and the test evaluation and expertise phase until December 2019 was contracted in March 2016.
The manufacturing efforts for the globally hardware rich programme set-up have been finalized step-wise within 2018. All hardware sets have been finished in time for the relevant foreseen test block. The P3.2 test campaign has been conducted from June 2018 to March 2019.

2.3 Development Logic

A key element of the development logic is the concept of an integrated demonstrator. The term "integration" is meant here in a two-fold way. On one hand the development activities are embedded in overall scenario of a flight application product, within the ETID project the so called flight engine image (FEI). On the other hand the hardware that is to be manufactured will be hot-fire tested in an integrated configuration demonstrating also the interaction among the subsystems during operation.
Starting from the mission requirements i.e. thrust, life, mixture ratio, for FEI provided by ESA, AGG has performed a trade-off study with respect to the architectural and functional design of the expander cycle upper stage engine, see [3]. Tab. 1 presents the main design driving requirements of FEI.
The FEI is based on a fully integrated cryogenic expander cycle engine architecture (see Fig. 3) that is operated with liquid hydrogen (LH2) and liquid oxygen (LOx).
The fuel mass flow for the regenerative circuit (RC) is provided by the pump-side of the hydrogen turbopump (HTP). While passing through the RC, the fuel is heated up to gaseous conditions before entering the turbines which are arranged in serial, i.e., the turbine of the HTP is passed first followed by the turbine of the oxygen turbopump (OTP). The operating point, the thrust level and the mixture ratio, of the fully integrated cryogenic expander cycle engine architecture is controlled by two bypass lines; the thrust is controlled by the thrust control valve (TCV) bypassing both HTP and the OTP turbines and the mixture ratio is controlled by the regulation valve (RGV) bypassing the OTP turbine.

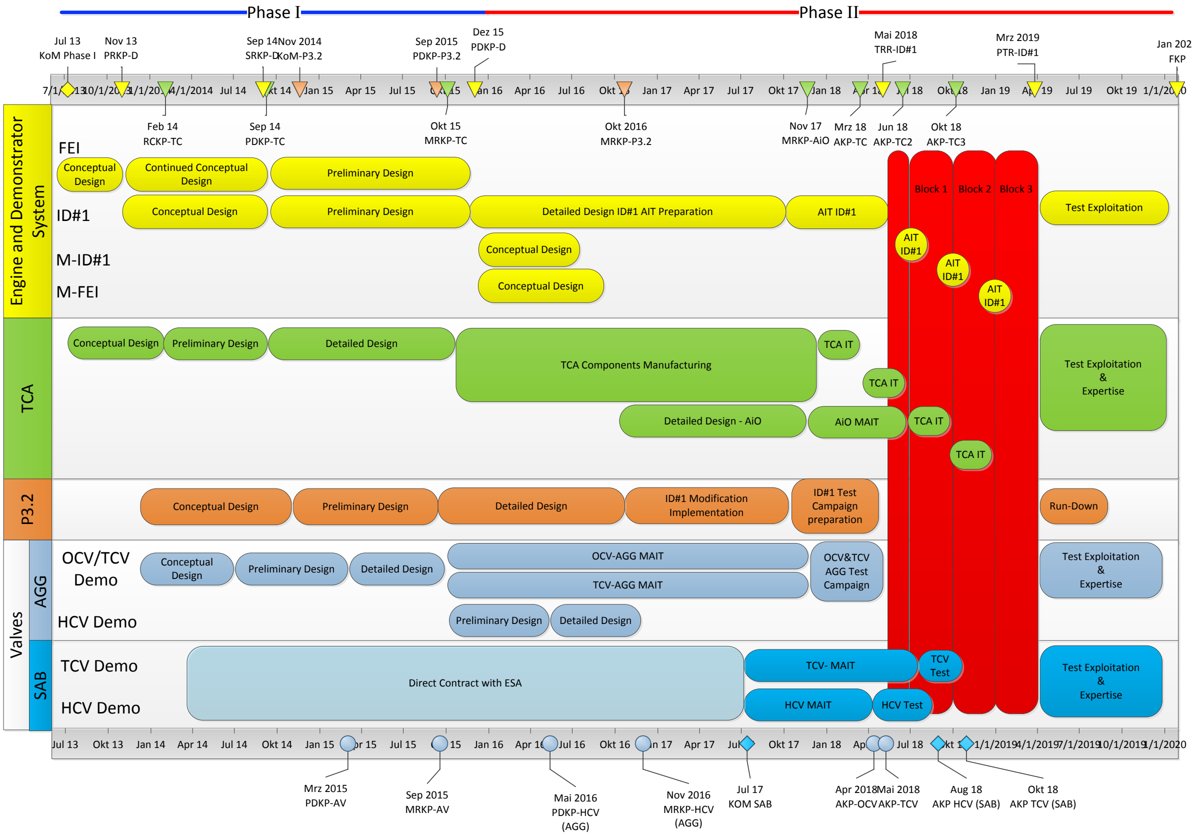

Figure 2: FLPP3 ETID project schedule

In Fig. 4 the PDKP-D status of the 3D representation of FEI is shown. The mechanical layout is characterized by a powerpack configuration with 180 degrees between hydrogen and the oxygen turbopumps. The powerpack is located at the side of the thrust chamber. The HTP and OTP are supported by attachments to the thrust chamber. The noticeable big bend radii of the engine lines are a consequence of the chosen line material (i.e. aluminium).

Table 1: FEI requirements

	Unit	**Value**
Thrust	kN	115
Mixture ratio	-	5.5
Specific Impulse	s	> 457
Thrust to Weight ratio	-	> 45
Engine height	m	< 2.5
Engine recurring price target (ec2013, cad 11, rank 30)	M€	< 3.0
Life (cumulated)	s	1400
Life (cycles)	-	5

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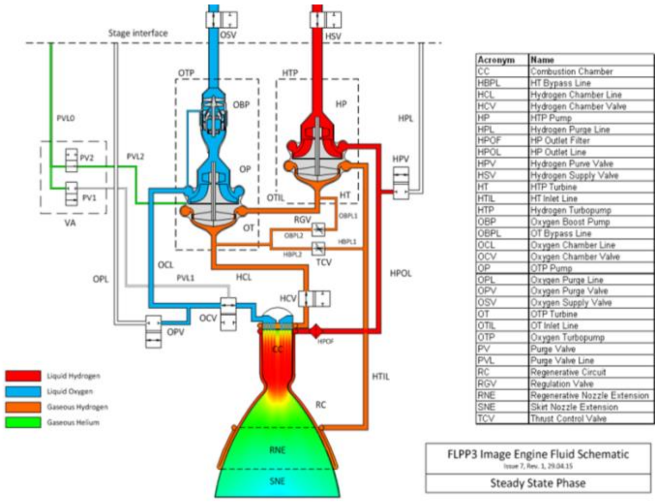

Acronym	Name
CC	Combustion Chamber
HBPL	HT Bypass Line
HCL	Hydrogen Chamber Line
HCV	Hydrogen Chamber Valve
HP	HTP Pump
HPL	Hydrogen Purge Line
HPOF	HP Outlet Filter
HPOL	HP Outlet Line
HPV	Hydrogen Purve Valve
HSV	Hydrogen Supply Valve
HT	HTP Turbine
HTIL	HT Inlet Line
HTP	Hydrogen Turbopump
OBP	Oxygen Boost Pump
OBPL	OT Bypass Line
OCL	Oxygen Chamber Line
OCV	Oxygen Chamber Valve
OP	OTP Pump
OPL	Oxygen Purge Line
OPV	Oxygen Purge Valve
OSV	Oxygen Supply Valve
OT	OTP Turbine
OTIL	OT Inlet Line
OTP	Oxygen Turbopump
PV	Purge Valve
PVL	Purge Valve Line
RC	Regenerative Circuit
RGV	Regulation Valve
RNE	Regenerative Nozzle Extension
SNE	Skirt Nozzle Extension
TCV	Thrust Control Valve

Figure 3: Functional cycle layout for FEI

Figure 4: FEI Design (PDKP-D status)

Following the integrated demonstrator approach the requirements for the subsystem level were derived from the functional and mechanical layout of FEI. A full functional specification tree for all engine subsystems has been elaborated. These subsystem specifications also include the specific requirements and constraints arising out of the demonstration character of the ETID project. An example for such a specific requirement is the maximum diameter limitation derived from the existing test bench setup at P3.2.

Figure 5: FLPP3 ETID products (FEI --> ETID --> ID#1)

Fig. 5 presents this logic of requirements derivation based on the different products investigated within the ETID project. The basis and the leading product for requirements, trade-offs, technology and design choices is the FEI that is shown on the left side of Fig. 5.

The ETID product shown in the middle is taking into account all specific requirements linked to the demonstration itself e.g. the P3.2 diameter constraint. One can identify that apart from the nozzle extension no difference persists

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between the FEI and ETID subsystems. This fact builts the core of the development logic of the project: ETID is in fact a demonstrator configuration testable at P3.2 which is combining all FEI subsystems.
In the budget and industrial frame of Phase 1 and Phase 2 of the project the ETID product (see middle of Fig. 5) containing all subsystems cannot be realized. Compared to ETID, a reduced scope has been contracted, named Integrated Demonstrator#1 (ID#1). Fig. 5 shows ID#1 on the right hand side. It consists of the following subsystems:

- TCA
    - Cardan spacer by AGG
    - Injector head by AGG
    - Combustion chamber by AGG
    - Nozzle extension by GKN
    - Laser ignition system by CTR
    - Direct spark ignition system by APP
- OCV by AGG
- TCV by AGG or SAB
- HCV by SAB

The technological content that is matured up to TRL5-6 in the frame of FLPP ETID by hot fire demonstration is allocated to these different subsystems.

3. Selected Technologies

Based on the logic and requirement elaboration described above several key technologies were identified that are required to reach the stringent cost and weight targets for FEI. Lessons learnt gained in the VINCI development fostered the choices made.

3.1 Thrust Chamber Assembly Technologies

For the thrust chamber assembly the main difference compared to the VINCI expander cycle layout is the allocation of the heat pick-up functionality to the CC and the NE. The sandwich nozzle, developed by GKN, provides a portion of the overall required heat-pick up to the hydrogen closing the full-expander engine cycle. This architectural change on TCA level leads to weight reduction potential. A reduction of the cylindrical length of the CC and a lower interface area ratio for the interface position between CC and NE is achieved capitalizing the lower area specific weight of the NE structure. This TCA architecture contributes to the targeted engine Thrust-to-weight ratio of >45.
Fig. 6 presents the demonstrator TCA hardware with the cost-efficient injector head and combustion chamber, the igniter ring and the metallic sandwich nozzle extension (regenerative and skirt part).

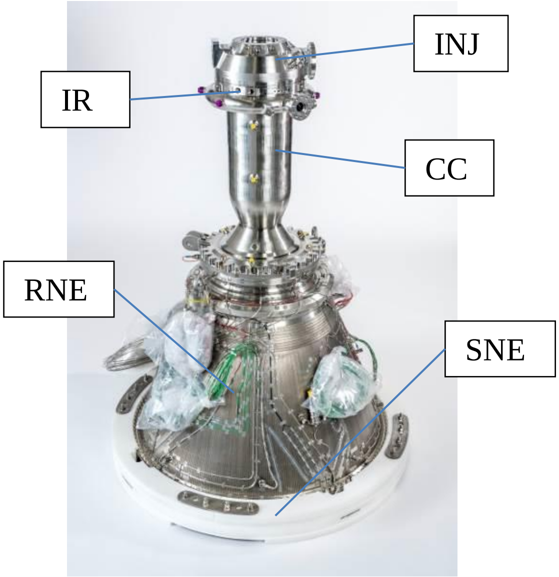

Figure 6: FLPP3 ETID TCA

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To achieve the cost and weight target values for the TCA the following specific technologies and design choices were identified for the TCA. A detailed description and elaboration on all these technologies will not be given herein However, the following bullet list shall give an overview of the number and variety of the investigated technologies in the frame of ETID project.

- Injector head - Variant 1
    - Cost efficient stainless steel injector with minimum weld seams
    - Integral milled baseplate incl. LOx-posts
    - No axial igniter access port
- Injector head - Variant 2
    - Additively manufactured ("3D-printed"): All-In-One injector
    - Significantly reduced cost compared to Variant 1
    - Significantly reduced lead time compared to Variant 1
- Combustion chamber liner and jacket
    - High strength electro-plated Nickel-Cobalt jacket
    - Low cost copper alloy liner
    - Hot gas wall design with increased heat-pick up
- Nozzle Extension
    - Stainless steel sandwich design
    - Contributing to TCA heat pick-up
    - Radiatively cooled skirt
- Ignition systems
    - Re-ignitable
    - Radial access via combustion chamber
    - Designed as line replaceable unit ("LRU") with operational advantage

3.1.1 Injector head

Two injector head variants have been design, manufactured and tested by AGG. Both feature innovative design solutions but differ in the basic manufacturing process philosophies. The injector head variant 1 design is based on a cost efficient forged stainless steel raw part. The injector head body is milled on high speed machines leading to short overall machining times. The internal injector head layout design is simplified significantly. As no axial igniter port is required in the ETID design only two electron beam weld seams are sufficient for the INJ assembly reducing the production cost substantially.

In order to lower the manufacturing cost and lead time even further compared to this milled injector head, additive manufacturing is applied for variant 2. The usually used injector head assembly consisting of hundreds of pieces is replaced by a 3D printed, so called, All-In-One injector design. The multifunctional additive part only needs to be finished via milling the interface surfaces. The cost benefits of such a short manufacturing sequence are obvious. This injector head variant 2 is described in more detail in [10].

3.1.2 Combustion chamber

As the choice of the raw material is one of the biggest drivers for total cost, a cost-efficient copper alloy has been selected in order to reach the demanding RC targets. The design challenge is here to achieve the required hot fire life time with the given derated material characteristics compared to high-performance copper alloy.

In addition to the raw material of the liner also the composition of the jacket material has been changed compared to VINCI and Vulcain II. A plated layer consisting of Nickel and Cobalt leads to higher strength, faster overall process and better weldability answering to lower mass and cost objectives.

With negligible additional cost circumferential grooves in the hot gas wall are manufactured increasing the heat pick up in the cylindrical part of the CC. Now following the successful demonstration of the performance of this feature an additional reduction in chamber length is envisaged.

Regarding the ignition system and the igniter port to the combustion chamber a new design approach is followed. Due to exchangeability and maintainability reasons the igniter is located radially at the combustion chamber at a dedicated igniter ring. This leads to a high gain in operability of the upper stage engine. Two igniter concepts are examined in the frame of FLPP ETID. An igniter based on laser technology and a so called direct spark ignition system. Both systems that allow for multiple in-flight re-ignitions feature a very low mass.

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3.1.3 Nozzle Extension

The ETID nozzle extension [5] features an upper regeneratively cooled stainless steel part (RNE), combined with a lower radiatively cooled metallic skirt section (SNE). The upper RNE part utilizes GKN's patented sandwich technology with a hydraulically balanced cooling circuit providing TCA system heat pick-up.

The key nozzle test objectives as well as main functional elements are; heat pick-up, pressure drop and integrity. An important function of the regenerative cooling circuit is its free hydraulic balance. This design facilitates heat pick-up, sufficient cooling of the sandwich hot gas wall and a high positioning of the outlet manifold, i.e. reducing mass on nozzle and TCA level. In Fig. 7, note that although the SNE stub is short, due to bench limitations, it still provides flight representative thermal expansion loads on the RNE/SNE interface flange.

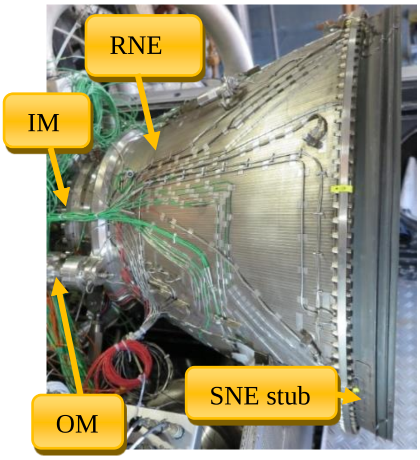

Figure 7: ETID NE at P3.2 bench after completed hot-fire test campaign (IM/OM – In-/outlet manifolds)

The manufacturing processes for GKN's patented laser welded sandwich technology have been further matured and improved, e.g. in the areas of; laser T-welding, additive manufacturing, milling processes, cone forming, in-process cleaning and repair methods which all are critical for a future flight development program.

3.1.4 Direct Spark Ignition System

The Direct Spark Ignition System (DSIS) is a spark plug based technology that is tested on ETID. Instead of using a spark to ignite a torch to ignite the engine, the spark plug is used to ignite a single CC injector element by sparking on the shear layer between the oxygen and hydrogen flow. Once the single injector element is ignited, it will ignite the remaining CC injectors. The principle was successfully demonstrated during the FFI P8 test bench campaign in September and October 2015.

The simplification of the ignition system to a (redundant) radially mounted spark plug has the potential for a significant system price and mass reduction without compromising on re-ignitability. Furthermore the concept allows for the radial mounting of the ignition system as described above to support a more cost efficient TCA design and, in addition, allowing for easier access to the ignition system.

Based on the success of the P8 campaign, APP-ArianeGroup continued the development of the system in preparation for the ETID ID#1 P3.2 campaign. On the ETID TCA, two opposite spark systems were mounted into the igniter ring, allowing to test different design variants.

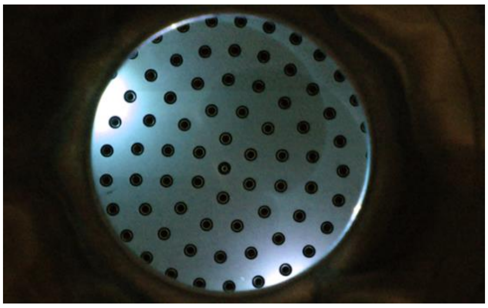

Figure 8: Direct sparking with 2 opposite DSIS at the ETID

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Two major observations from the P8 test campaign have been implemented in the DSIS design for the ETID ID #1 campaign.

The first is a refinement of the sparking location. The P8 campaign showed that the location is linked to the moment of ignition after the oxygen valve is opened. Hence, the spark tip has been moved inward such that the diverging oxygen jet shear layer reaches the spark tip earlier after oxygen valve opening.

The second observation that has been taken into account is the thermal loading of the spark plug tip. Thermal analysis and the short duration burns at the P8 test stand showed that the thermal loading might be what is beyond the spark plug's capability. To reduce the thermal loading of the spark plug tip, two types of protective covers have been designed, each allow for a gas flushing for additional cooling.

3.1.5 Laser Ignition System

The laser ignition system is located radially at the igniter ring of the combustion chamber. The laser beam is guided into the combustion chamber volume through an optical access tube featuring a brazed sapphire focusing lens as high temperature and high pressure capable interface. An additional sapphire window at the outer end of the tube is used as safety barrier. Two laser heads had been mounted onto the igniter ring in order to provide redundant ignition capability.

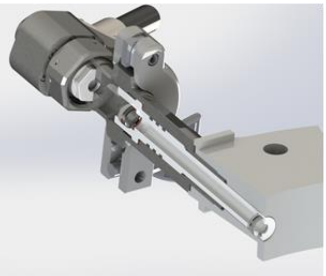

Figure 9: Laser optical access tube

3.2 Valves Technologies

The requirement for the FEI engine layout is that all engine valves are electrically actuated with the upper stage electrical supply voltage of 55V DC. In the frame of FLPP3 ETID project, AGG designs and manufactures demonstrators for the oxygen chamber valves (OCV) and the regulation valves (TCV and RGV) including its electrical controller. The partner Safran Aero Boosters studied a valves (RGV, TCV, OCV, HCV, OPV, HPV) and controller package for a cryogenic upper stage expander cycle engine.

3.2.1 SAB Valves

Prototypes were developed of the Hydrogen Chamber Valve (HCV), Thrust Control Valve (TCV) and Valve Controller Unit (VCU - collaboration with Thales Alenia Space) for the ETID demonstrator.

Figure 10: From the left HCV TCV and VCU respectively

HCV is a linear shut-off poppet valve with 90-degrees elbow. Speed control is possible thanks to the presence of an elastic system at the end-stop. The flow body is optimized to be manufactured in AM as it is the external cover and

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connector support for TCV. Casted HCV flow body was finally used for qualification and ETID prototypes due to planning constraints.

Table 2: HCV requirements

HCV(shut-off)	**Unit**	**Value**
Hydraulic section	mm²	0…3000
Pressure	bar	70
Temperature	K	170
Internal leakage (GHe)	Ncm³/s	≤ 100

Table 3: TCV requirements

TCV(control)	**Unit**	**Value**
Hydraulic section - Design	mm²	1…80
Hydraulic section - Operating	mm²	28…55
Hydraulic section - Reference	mm²	43
Pressure	bar	160
Temperature	K	190
Hydraulic Resolution	%	≤ 0.1
Hydraulic repeatability	%	≤ 0.5

TCV is a high resolution regulation valve (resolution <0.1% of total stroke at maximum design load in cold condition measured during qualification). The 90-degree elbow maximizes the regulation stroke for a movable long stroke hollow ball. The dry lubricated Harmonic Drive gearbox gives a no backlash transmission.

AC brushless motor designed for full triple redundancy concurrently with redundancy of resolver sensors and a specific algorithm including up to 5 “Failure Detection Isolation & Recovery” (FDIR) functions capable of detecting a single failure in less than 50-100 ms guarantee fault-tolerance with no impact on the valve position.

Capable of controlling up to 6 valves, the VCU is based on a modular architecture; ETID VCU functional model is equipped for 3 valves, during the tests it supplies and controls 2 valves (HCV & TCV).

3.2.2 AGG Valve s

The picture below shows the first hardware of the OCV/TCV/RGV coaxial demonstrator valve mounted on the tooling specifically designed for the cold test campaign to be performed at AGG premises. This valve demonstrator features a co-axial design with the electro-actuator located in the outer part of the internal volume of the valve.

There are three different applications of this electric demonstrator motor valve: as OCV, TCV and RGV. The design of the motor valve was selected in a way that all three valve types are identical except for a flow part which is exchangeable with low effort due to a common interface to the valve. The OCV is a shut-off valve located in the main oxygen line of the demonstrator engine. The task of the OCV is to enable or to stop the oxygen mass flow into the thrust chamber. For this valve no regulation of the mass flow is required. The valve’s only function is to close the line leak tight. On the contrary, the TCV and RGV are regulation GH2 valves which consist of a flow part that has the ability to adjust the GH2 mass flow in order to regulate the turbine speed. A streaming cone has been designed for the OCV functionality with the purpose to allow a smooth transition of the LOx flow from the inlet to the main body of the valve. A mass flow regulation cartridge has been designed for the TCV/RGV (both valves are sharing an identical design) which includes axial slots in such a way to match the required mass flow accuracy.

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Figure 11: OCV/TCV/RGV demonstrator valve mounted for the cold test campaign (the geometry of the inlet flange is manufactured using an ALM technique)

The technological content linked to this valve is as follows:

- A fully redundant brushless DC electromotor.
- A reluctance motor brake to reach bi-stable valve behaviour.
- A resolver for measuring angular position. The resolver acts on the reluctance principle.
- A linear variable differential transformer for shutter position detection.
- A ball screw gear for the transmission of the rotatory motion of the motor to the linear motion of the shutter.
- The flow part features a movable, pressure balanced tubular shutter with a polymeric valve main seat.
- To keep the internal leakage values within requirements, a polymeric valve seat made of PEEK has been selected.
- Internally to the valve, a streaming cone (for an OCV function) or a mass flow regulation cartridge (for a TCV/RGV function) can be featured.
- The dynamic sealing systems of the valve are arranged as such that all external leakages will be collected in the sealing chambers and carried off by the collecting lines.
- The inlet flange of the valve has been manufactured using an ALM (Additive Layer Manufacturing) technique.

4. Test Campaign at P3.2

Within the ETID project a significant amount of hardware has been manufactured in order to maximize the gain of knowledge on a broad range of technologies and at the same time reduce the risk of losing test opportunities in case of potential technological failures.
In total, the following test article hardware sets have been manufactured by AGG and its partners:

- 3 different injector heads
- 3 different combustion chambers
- 2 identical regenerative nozzle extensions
- 2 different skirt nozzle extensions
- 4 different DSIS protection covers
- 2 different thrust control valves
- 1 hydrogen chamber valve
- 1 oxygen chamber valve
- 1 redundant laser ignition system
- 1 redundant direct spark ignition system

In addition to this hardware intense approach, a stringent spare parts policy for off-the-shelf hardware has been followed. This collection of subsystems has been combined to four ETID test configurations. The TRR was performed on 03.05.2018 and the PTR at the 27.03.2019, summing up to 11 months of continuous test campaign.
In total, 2707 s of hot run time were performed in 23 hot-fire cycles. The team was able to perform the campaign with an average of one successful test per 6.1 working days. The exchange of hardware, meaning a full bench re-configuration, was done in an average of 34 days.

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The objectives of the hot-fire testing were:

- Ignition System (LIS, DSIS) tests under full altitude simulation test facility configuration
- Run-In of facility, freezing of baseline start-up sequence up to REF first operation point with full altitude simulation test facility configuration. Start-up- as engine like as possible.
- Run-In of facility to OP operation points for confirmation of bench control loop accuracy/reproducibility and facility operation
- Run in of CC Hardware for stabilization of heat pick up
- Exploration of performance parameters. Measure all needed data for evaluation i.e. heat pick-up performance, comparison of grooved and smooth chamber wall (heat pick-up and pressure drop) of CC and NE, combustion efficiency. Variation of injected hydrogen temperature as the most uncertain parameter according to the specification, full DoE approach.
- Thermomechanical behaviour of components (long duration tests for thermal stabilization)
- Artificially over-cooled CC and RNE, measure all needed data for evaluation and comparison.
- RNE/SNE characterization, measure all needed data
- Anchoring of analytical models for the TCA and valves, measure all needed data for tool validation over the whole design envelope
- Margin tests outside the design domain
- Measure thrust which not only allowed to characterize the load point dependent performance of the designed hardware but also to explore the effect of internal water condensation on specific impulse by artificially over-cooling of the TCA
- Characterization of TCVs, measure all needed data e.g. pressure drop along the valve, evaluate el / RVCU parameter from controller.
- Characterization of HCV, measure all needed data e.g. pressure drop along the valve, evaluate el / RVCU parameter from controller.
- Characterization of OCV, measure all needed data e.g. pressure drop along the valve, evaluate el / RVCU parameter from controller.

During the very successful campaign at the P3.2 facility in Lampoldshausen all above listed objectives were reached. The embarked technologies for the thrust chamber assembly and the electro-driven valves, performed faultlessly and with the expected range of performances and behaviours. These extraordinary promising results are represented by 80 GB of highly compressed binary test data. Important lessons learnt have been collected that will allow to even further optimize specific features for potential future flight application, some of which are further explained below.

Fig. 12 shows all tested operating points together with the targeted design domain. To demonstrate margins of ETID hardware specific operation points were tested also well outside of the design domain. The margins to maximum heat load and max hot gas wall temperature were tested by load points at the upper right corner of the chamber pressure (pC) – mixture ratio (O/F) domain. These points are considered as critical concerning the hot gas wall liner life. Compared to the REF conditions of pC=56 bar and O/F =5.5, the chamber pressure was successfully increased up to 70 bar at a mixture ratio of 6.1 without any visual effect on the hardware. The margins to maximum pressure in the engine at the cooling channel inlet were successfully tested at high chamber pressures and low mixture ratios of up to pC=73 bar and O/F =4.7. These challenging conditions were sustained by the low cost ETID combustion chamber designs.

Low pressure and low O/F are considered as the operation points with maximum condensation of water at the chamber and nozzle hot gas walls. For these operation points the engine domain is lowered as far as possible by FEI simulation of RGV and TCV variation in a wide parameter range (0% - 100%). However the limit is a pC of 35 bar due to unstarting risk of the altitude simulation unit of the P3.2. Low chamber pressures are also being the operation points with the lowest delta pressure along the injector for LOx (low O/F) and H2 (high O/F). This is critical from a chugging and HF point of view based on the fact that the combustion chamber and the injector are only weekly de-coupled. No signs of these phenomena could be observed during hot-fire testing of ETID proving the combustion stability of both injector heads.

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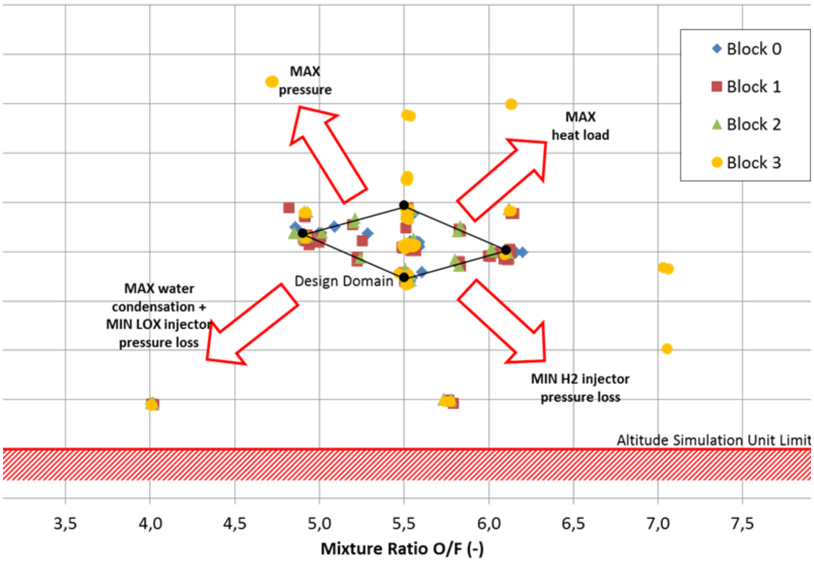

Figure 12: ETID operating points with design domain and explained failure axes

Fig. 13 gives an overview of the ETID run-in test configuration as seen from above the vacuum chamber of P3.2 test bench. A total number of 226 measurements are installed on the Run-In configuration. This amount has been further increased to 284 measurements for the following configurations.

Figure 13: ETID run-in configuration mounted into P3.2

Figure 14: ETID in operation at P3.2 *

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The AGG electro-driven valves have shown the expected performances, both for shut-off mode and regulation mode in the full and extended tested operating domain. The electrical motor design philosophy proofed to be a key change for the start-up and shutdown transients design of rocket engine. The now verified high reproducibility can be subsequently exploited for the optimization of the rocket engine transients.

The RNE of GKN has been the only hardware that has been used throughout the 23 hot cycles of ETID to accumulate a maximum number of cycles, whereas two different SNE configurations were tested. The ETID NE has proven major technology steps, such as; heat pick-up, pressure drop, hydraulic balance, condensation robustness, mass reduction potential, contour and interfaces within tolerances, as well as a robust design capable of withstanding the loads. By completing the test campaign the technology has successfully proven more than four times the number of hot cycles required for a flight application.

It is notable that towards the end of the campaign the test envelope was stretched far outside the design envelope. The thrust and system pressure levels were increased by 30% outside of the design envelope. The nozzle design showed robust performance while operating under the increased temperature and pressure loads.

At the time of writing the work of evaluating test data and validating the design tools is ongoing. Preliminary results show that pressure drop and flame wall temperatures are within expected ranges, whereas the design tools needs to be tuned for better agreement of heat pick-up. This was one of the main objectives for GKN in performing the P3.2 ETID TCA tests, i.e. to gather test data in order to tune design tools for high pressure cooling systems.

Fig. 15 shows an example of the RNE flame wall temperature using values from testing and from pre-test CFD analyses. The analysis results match the measured data well, especially when considering the standard deviation.

The ETID test campaign has delivered data sufficient to fulfil NE test objectives. Furthermore, the campaign has proven the ETID nozzle technology in several aspects:

- Function in terms of providing thrust, system heat pick-up and fulfilling pressure drop budget
- Manufacturing maturation of critical operations and processes
- Cost effectiveness due to improved design and manufacturing processes
- Robustness & life endurance incl. extreme testing

The ETID RNE has successfully completed more than four times the number of hot cycles required for a flight application. Hence, the ETID NE sandwich technology is ready to target future upper stage flight applications.

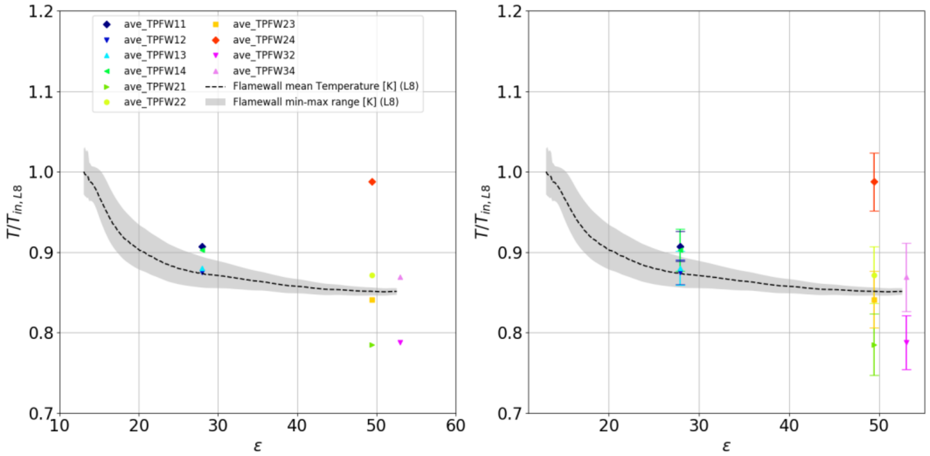

Figure 15: Measured RNE flame wall temperatures (dots) and pre-test CFD values (dotted line and shaded area) vs. area-ratio (ε). Values normalized with inlet temperature.

For the DSIS and its originally foreseen thermal protection features multiple successful ignitions were achieved during the ETID test campaign showing ignition delays within acceptable limits and in addition reduced scattering of the engine ignition delay. During the campaign, additional thermal protection improvements were implemented, finally resulting in two design options that could withstand a total of 710 s of engine burn duration. These were a slightly further retracted tip and a cover with fully circumferential gas flushing (see Fig. 16).

Unfortunately with the modified thermal protection successful ignition was not demonstrated. However, with the P3.2 test campaign results the design can be matured for the FEI engine to optimize the DSIS with respect to successful engine ignition and thermal survivability.

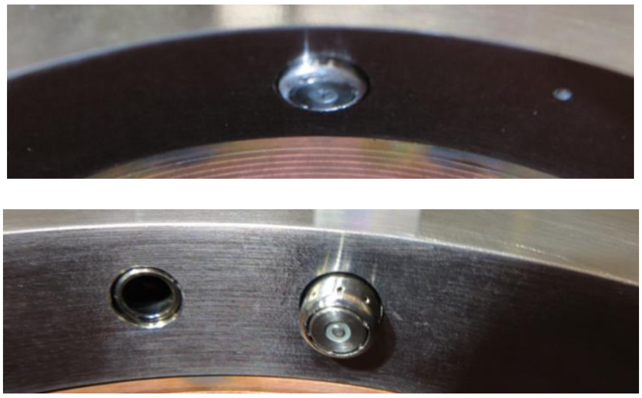

Figure 16: Two designs of the DSIS thermal protection that survived 710 s of hot run

Laser ignition has been tested successfully during the ETID campaign demonstrating high reliability of ignition. During the first test sequences it was found that the sapphire window has a certain susceptibility to suffer cracks due to thermal shocks when purging the combustion chamber after shutdown. These cracks were found to propagate from microscopic chips on the edges of the polished front surface towards the centre of the lens. A solution was found in mounting a protection ring at the chamber side of the lens with a centre hole just large enough to let the laser beam pass without attenuation. No further lens damage was observed during the rest of the campaign.

Figure 17: Optical access tube and laser plasma

The laser was operated in burst mode at a repetition rate of 50 Hz for 50 pulses (see Fig. 18). At 0.3 seconds after sequence start, the trigger for the both laser igniters is set, starting the burst of laser pulses (red and black spiked lines). Depending on the time of opening of the fuel valves and the arrival of fuel at the injector, ignition is achieved after about 0.5 seconds in the burst corresponding to between 1 and 15 pulses after achieving ignitable conditions at the laser plasma location.

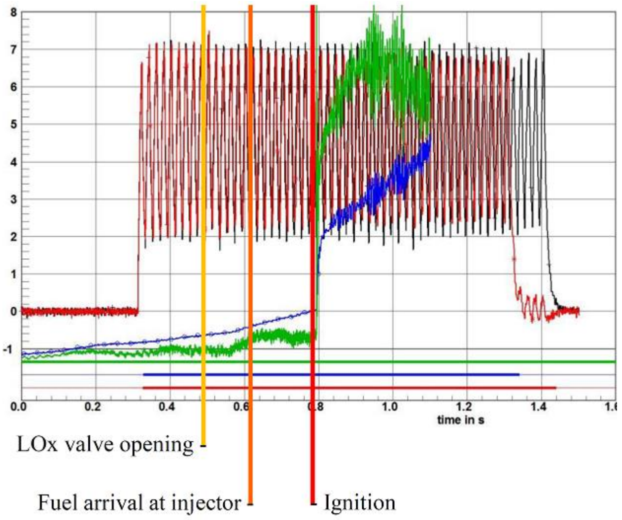

Figure 18: Laser igniter burst mode sequence

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The electro-driven valve hardware of SAB has successfully completed the qualification (May-September 2018) and the ETID (November 2018 - March 2019) test campaigns. The AC brushless motor design for full triple redundancy concurrently with redundancy of resolver sensors and a specific algorithm including up to 5 “Failure Detection Isolation & Recovery” (FDIR) functions capable of detecting a single failure in less than 50-100 ms guarantee fault-tolerance with no impact on the valve position (see Fig. 19).

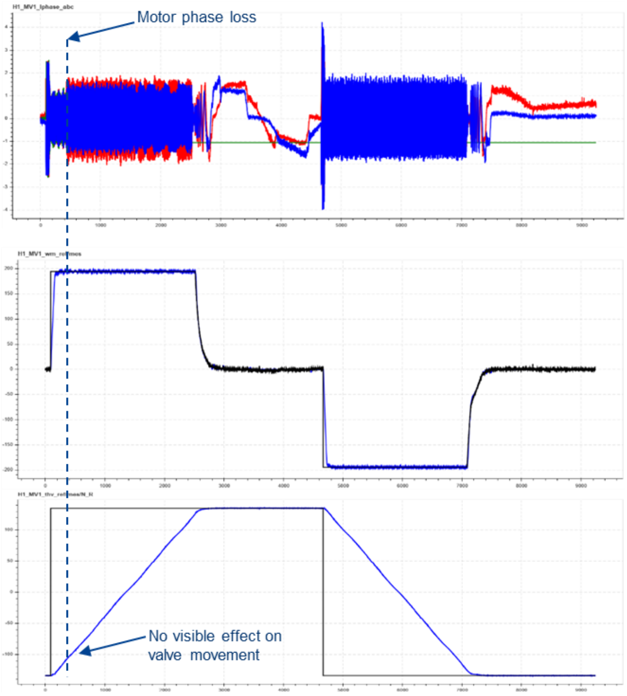

Figure 19: Fault-tolerance demonstration test result

The SAB valve concepts demonstrated in the ETID campaign that electrification can be performed maintaining the mass target of pneumatic valves while introducing innovative technologies.
TCV and HCV and their control chain showed good behaviour repeatability on the demonstrator maintaining expected performances at all operative points tested.

5. Conclusion & Outlook

The ETID test campaign has delivered a significant data base to fulfil all foreseen test objectives. The key design performances of the tested hardware sets have been met. The structural integrity and life time of the TCA components even exceeded the expectations and margins have been verified by the test campaign.
In the following months until end of 2019 a detailed test data evaluation and a non-destructive expertise of the hardware sets will bring the embarked ETID technologies to TRL 5-6. This will serve as an important step towards an application of chosen technologies to future variants of the European launchers.

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CTR	for the laser ignition system
APP	for the direct spark ignition system
SAB	for the HCV and TCV
DLR	for the test bench P3.2
NAMMO	for the engine lines
CTU	for the HMS approaches

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