Test operations on the Upper Liquid Propulsion Module (ULPM) of the new European launcher Ariane 6 on the upper stage test facility P5.2

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1. Introduction

The German Aerospace Centre (DLR) Lampoldshausen designs, builds, manages and operates on behalf of the European Space Agency (ESA) several ESA owned test facilities on the DLR test site at Lampoldshausen. These test facilities owned by ESA and operated by the DLR Lampoldshausen are key strategic assets for the European Launcher Sector and the independent European access to space.

The existing infrastructure and test facilities allow the performance of test activities for research and development as well as production purposes for the European Launchers.

The ESA owned test facilities are the test benches P3, P4, P5 and P5.2. On the test facility P3 engine thrust chambers or engine components are tested. The high-altitude simulation test facility P4 with the two test positions P4.1 and P4.2 is used for upper stage engine testing under high altitude simulation conditions. The test position P4.1 is dedicated to cryogenic upper stage engines, currently focusing on the Vinci® engine; the test position P4.2 is dedicated to storable upper stage engines, currently used for the Ariane 6 upper kick stage Storable Propellant Engine (SPE). Tests on the Ariane 5 cryogenic main stage engine Vulcain® 2 and on the Ariane 6 cryogenic main stage engine Vulcain® 2.1 are carried out on the test facility P5. The new upper stage test facility P5.2, where the Ariane 6 upper stage is tested, has been erected close to the P5, as several subsystems of the P5 will also be used for the operation of the P5.2.

Since decades it is the first time that an upper stage test facility has been erected and operated in Europe. This paper provides in a first part a description of the P5.2 test facility in the hot run test configuration. In the second part the campaign with the Ariane 6 upper stage, the so-called Upper Liquid Propulsion Module (ULPM) is described and an overview on the operations during the test preparation and actual test phases will be given. In a third part main challenges in operations for testing the Ariane 6 Upper Stage will be presented and also it will be shown how these challenges have been managed with. Main results and lessons learnt of the test campaign from operational point of view will also be summarized.

2. Overview of ESA facilities managed and operated by DLR [1]

The P3 test facility is an ESA facility, managed and operated by DLR Lampoldshausen under the ESA-DLR Asset Agreement. The test facility P3 (Fig. 1) is capable of engine component testing with mass flows up to 330kg/s and interface pressures up to 280bar. Th P3 has the possibility of testing under high-altitude simulation capability and uses the propellant combination of liquid oxygen with liquid hydrogen or liquid methane / liquid natural gas.

Fig. 1: ESA P3 test facility

The ESA owned test facility P4 (Fig. 2) is for testing of upper stage engines under high altitude simulation. The test facility P4 has two test positions, one being the test position P4.1 with cryogenic propellants liquid oxygen (LOX) and liquid hydrogen (LH2) up to 250kN thrust range and one being the test position P4.2 with storable propellants Dinitrogen tetroxide (N2O4) and Monomethyl hydrazine (MMH) up to 30kN thrust range. The steam generator system is used to power both altitude simulation systems and has a capacity of 226kg/s water steam.

Fig. 2: ESA P4 test facility

The ESA owned test facility P5 (Fig. 3) is for launcher main stage engine tests. The tests are done under sea level conditions with liquid oxygen and liquid hydrogen. An extension to liquid methane and liquid natural gas is currently under installation. The possible thrust range is up to 4.000kN.

Fig. 3: Test site DLR Lampoldshausen ESA P5 test facility in operation for Vulcain® 2.1 testing

The ESA owned test facility P5.2 (Fig. 4) is a versatile test facility. The P5.2 is used for cryogenic upper stages testing with LOX and LH2. On October 5th, 2022 the new Ariane 6 ULPM successfully completed its first hot-fire test.

Fig. 4: ESA P5.2 test facility for Upper Stage testing

The operation of the test facilities needs a high amount of logistics and fluid supply. This is done centrally at DLR Lampoldshausen for the following elements:

- Central gaseous nitrogen (GN2) production from liquid nitrogen (LN2)
- Central gaseous helium (GHe) supply
- Central gaseous hydrogen (GH2) production from LH2
- Central storages for LOX and LH2
- Central cooling water supply
- Storage areas for storable propellants

The electrical supply is comprised of the nominal supply as well as the uninterruptable power supply (battery buffering systems) and an emergency power supply (emergency diesel generator).

The operational services are completed by the provision of command rooms and real time computer systems for measurement, command and control. There are integration and assembly buildings as well as storage areas for spare parts. Workshops and clean rooms and processing facilities for neutralization of the storable propellant wastes are also available.

DLR Lampoldshausen has since the start of the Ariane program in the 1970s played a central role in testing of the Ariane launchers propulsion systems. Since this time the experience, know-how and capabilities increased continuously and makes DLR Lampoldshausen the central site where are all testing of liquid propellant space propulsion can be done. All test facilities are unique, the functions are developed and designed by DLR Lampoldshausen.

3. Overview of ESA test facility P5.2 [2]

The P5.2 has the basic function of supplying the Ariane 6 Upper Stage, the so-called Upper Liquid Propulsion Module (ULPM), with all needed I/F in specified and controlled conditions. Furthermore, the bench P5.2 has to ensure the safety of the overall test.

The arrangement of the P5.2 test bench building has three main parts:

- A test cell as steel structure in front of a concrete safety wall. The ULPM is installed in the test cell and connected to the different I/F for fluid supply, command and measurement systems.
- Below the test cell a concrete chute with gas jet guiding system for hot gas exhaust of Vinci® engine and
- A concrete building behind the safety wall with five levels for gaseous panels (Fig. 6), Measurement, Control and Command (MCC) elements and auxiliary systems.

Next to the P5.2 building high-pressure bottles are stored. To handle the cryogenic exhaust, a flare stack on LH2 side and a LOX basin (gravel pit) are installed. Fig. 5 shows different sections of the P5.2 test facility.

The test facility is equipped with a crane for lateral loading of the ULPM into the test cell. Inside the test cell a support structure is installed, functioning as mechanical I/F and also needed to take the mass load of the whole filled upper stage as well as the thrust of the Vinci® engine during operation.

On the south side and in an angle of 45° to the building a concrete wall is erected in order to protect other test benches in the vicinity (closest is the test bench P5 used for Vulcain® 2.1 engine development and in the future for the Prometheus engine) in case of any safety-related incident at P5.2.

3.1 Fluid supply systems

LH2 propellant is routed via transfer lines from P5 tank via a vacuum insulated transfer line inside a concrete channel to the P5.2 forecourt. A safety shut-off valve interrupts the supply of propellant in case of need just in front of the safety wall. After passing the safety wall the LH2 enters the propellant supply tank loading panel which measures the flow and determine the flow rate towards the ULPM interface.

LOX propellant is routed via a vacuum insulated transfer line from LOX storage area towards P5.2. On the north platform after passing the safety isolation valve the LOX is flowing through the LOX propellant loading panel towards the ULPM interface.

The gaseous supply needed on P5.2 is containing

- Gaseous nitrogen
- Gaseous helium
- Gaseous hydrogen
- Gaseous oxygen
- Propane

The gases are used for pressurization, conditioning and venting purposes. Propane is needed for the flare stack of P5.2.

The supply is organized via the test benches P3 and P5 as well as directly from the central supply area available on site.

High-pressure bottles located at the test bench P3 are connected via a PN320 bar line ("backbone line") to the P5.2 and via a PN800 bar line to provide GHe for the ULPM high-pressure helium sphere filling. A pressure reduction station installed at the test bench P3 provides the needed pressure control (720bar to 230bar). The high-pressure bottles can be filled via a 720bar filling line connecting the high-pressure compressor station to the P3.

Fig. 5: Test bench P5.2 from different angles: high-pressure bottles and concrete building (top), chute area and crane device (middle), LOX basin and flare stack (bottom)


Fig. 6: View of P5.2 gaseous panel room

Pressurized cooling water is supplied from the test bench P5 via a cooling water line. The cooling water line enters the earth covered cooling water section behind the safety wall of P5.2 and is ducted via the under floor through the safety wall into the test cell. The cooling water distribution of the exhaust system is routed via the chute to the exhaust silencer tube in the chute (Fig. 7). This system ducts the exhaust gases of the Vinci® engine away from the test specimen. The exhaust tube serves as an acoustic damping device lowering the overall acoustic environment of the ULPM during hot firing tests.


Fig. 7: View of P5.2 exhaust jet guiding system

3.2 Building installations

On the backside of the concrete safety wall the P5.2 building contains the needed rooms and space for

- Auxiliary electrical power supply and distribution system
- Water distribution in the lowest floor level
- Gaseous panels on two floor level
- Measurement and command and control systems on two floors
- Workshop

On the frontside of the concrete safety wall is the test cell. The four sides of the test cell consist of one concrete safety wall and three metal walls equipped with shutter doors for being open at test and being opened for test specimen integration.

The steel structure of the test cell provides sufficient space for test specimen. The roof of the test cell is equipped with openings for H2 ventilation in case of low leakages.

On the south east side of the test cell the test cell can be entered by an at-grade access level in order to allow handling and mounting activities under the ULPM (e.g. mounting exhaust adapters, exchange of engine, etc.).

The floor takes the static load of the trolley and is equipped with a covering in order to close the exhaust opening for loading test configuration.

Plates on the bottom floor can be partially uncovered in order to make the bottom transparent for any cryogenic leakage of the test specimen.

The test cell structure contains all necessary components in order

- to fix the upper stage by a sufficient stiff thrust frame
- to allow hot run of the ULPM (e.g. by opening the test cell walls at three sides by shutter doors)
- to perform surveillance tasks of the upper stage (video etc.) during all the time
- to allow dismounting and mounting of the upper stage with the bridge crane installed inside the test cell
- to allow handling and dismounting of subcomponents and adjacent structures of the upper stage by providing necessary platforms (partially moveable)
- to perform filling / draining and hot run tests
- to operate the test specimen during other than test phase at suitable configuration and condition (e. g. storage between test)
- to provide and evacuate cryogenic fluids by fluid piping for as well LOX and LH2 propellants as auxiliary fluids
- to monitor the atmosphere inside the test cell for GH2 or GOX pollution
- to have access on the other floor levels.

3.3 P5.2 MCC system

The P5.2 Measurement Control and Command system (MCC) is based on current P5 MCC system. The P5.2 computer system is independent from P5 MCC system and the P5.2 has an own time management system based on a received GPS signal. It consists of a front end and a midlevel back end system. Nevertheless, some status signals are exchanged between P5 and P5.2 computer system. Wrt. ULPM electronic control connection an electronic ground control system (CBP5.2) is interfacing the ULPM.

For safety reason some direct access to ULPM stage valve and measurements is needed from P5.2 MCC.

In case of degraded function of P5.2 MCC the control is taken over by the Emergency Safety System (ESS) which provides the necessary access for stopping the test and bringing the test facility and the ULPM in safe condition.

Part of the fluid supply system of P5.2 is under control of Utility Management System (UMS) which is operating independently from P5/P5.2 MCC. The necessary terminals are positioned in the building M8 control and command room, for test preparation in the terminal room in the first floor.

A general function of the P5.2 MCC is also the acquisition and archiving of bench data as well as safety critical upper stage data. During test operation the P5.2 MCC runs several hundred sequences and redlines in order to command and supervise the test safely. Fig. 8 shows the MCC front end and signal conditioning room at P5.2.

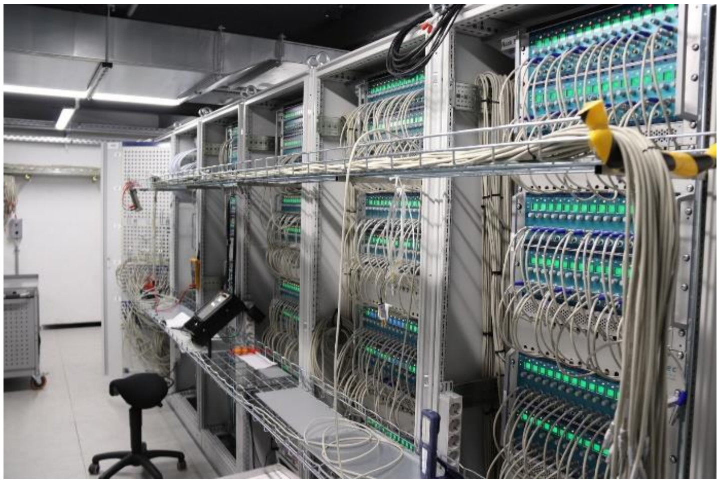

Fig. 8: View of P5.2 front end room of P5.2 MCC

3.4 Safety systems

The bench is completed by a set of safety features such as e.g.

- Fire detection system
- Fire-fighting systems
- Hydrogen detection system
- Oxygen detection system
- Alarm systems
- Video surveillance

3.5 Bench infrastructure

A specific GN2 production facility D57a is available in order to provide the needed amount of GN2 flushing flow for the P5.2 ULPM tests. The LN2 storage will provide sufficient amount of LN2 which will be evaporated in two (each one redundant) evaporation circuits, one low pressure and one high-pressure.

For the high-pressure the LN2 is pumped to the needed pressure value. The produced GN2 is supplied via two rigid pipe lines to P5.2 test bench.

The GN2 production facility is operated in remote control mode. Between tests the trailer unloading station allows the unloading of LN2 trailer for refilling of the LN2 storage.

From building M8 the control of a test on P5.2 is performed. From all test site systems participating to the ULPM test the necessary information via measurement systems or video systems are delivered to the test team.

The control building M8 protects the test team against the hazards of test performance. Some offices allow preparation of test work. Conditioning work on the measurement system (e.g. amplifier) is done inside the M8 building. During test the control of test execution will be performed by the team placed within the P5 control room. Safety staff as well as customer I/F and test specimen project I/F people are completing the DLR test team inside the control room for performing the test. The important infrastructure is shown in Fig. 9.

The electrical power supply station D59 provides the necessary overall electrical power for P5.2 test operation. The 230VDC network is set up on three availability levels. (1) the standard supply is directly connected to the public power supply and powering all electrical elements of the test bench, its supporting facilities and the ULPM, (2) a diesel fueled power generator supplies all safety critical installations, in particular the measurement acquisition, command and control systems and (3) an uninterruptible power supply (UPS) protects the critical systems during stand-by of the bench against short time failures of the public network. In order to increase the safety level, the critical electrical systems are connected to two independent UPS. For maximum safety during operation of the test bench and the ULPM, i.e. during a test day, the diesel generator is activated and electrically synchronized with the public network in order to be able to provide the needed electrical power throughout the day. A diesel refilling capacity is permanently available on the DLR test site for any case of immediate demand.

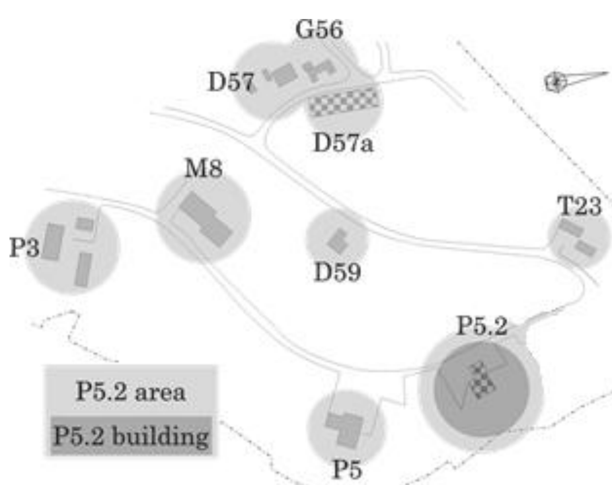

Fig. 9: P5.2 incorporation on site using supply and support functions from other benches and installations

4. Generic description of the test campaign

Before a test campaign with an actual test specimen can be started on a newly build test facility, a so-called reception phase of all bench installations and systems is done. This reception is divided in sub-phases called R0, R1, R2 and R3, see Fig. 10.

The R0 phase corresponds to a contractual acceptance under the supplier's responsibility (e.g. conformity checks relative to the specifications and plans).

In the R1 to R3 acceptance phases the characteristics of all bench installations and systems are tested and verified against the requirements coming from the SIE (Spécification d'Installation d'Essais – Test facility specification). The methods of acceptance have been defined in the CVM (Compliance and Verification Matrix). Hereby three different possible methods of acceptance are existing: Analysis, Design and Test. Every acceptance test has been defined in the Acceptance Test Plan. Each test has its own test sheet describing all conditions, boundaries and the requirements.

The R1 phase contains above all successive sequence of the concerned subsystems. The acceptance test and procedures are defined by and also accomplished under the responsibility of the respective project group. The aim of the tests shall be to check the function of the system in the final configuration with inert media.

The R2 phase acceptance tests and procedures are defined by and also accomplished under the responsibility of the respective project group. The objective of the acceptance tests shall be to confirm the operational availability of the test bench. These acceptance tests are provided for the acceptance of a complete J0-chronology. Here the engine is replaced by a model (mock-up).

The R3 phase is the performance of an engine hot-fire test. In addition to the R2 phase the performance capability of an engine hot-fire test has to be demonstrated (e.g. performance of start-up, steady state and shut-down transient).

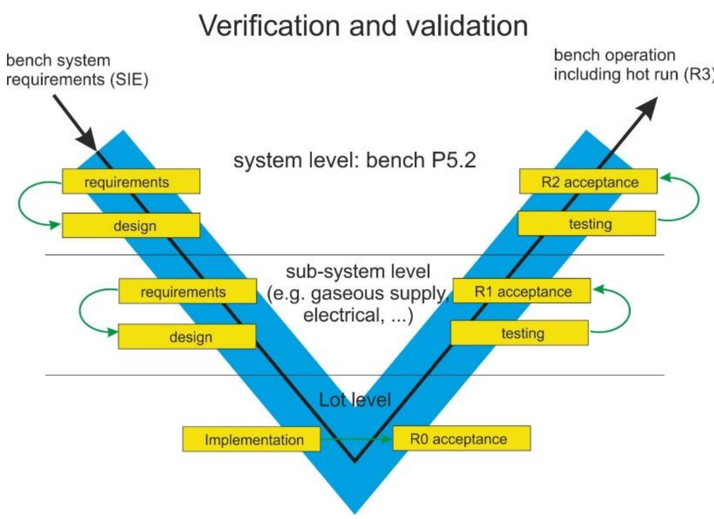

Fig. 10: Validation/Acceptance Scheme for Space Engine Test Facilities (taken from Ref. [2])

The reception phase R1/R2 is completed by a so-called TQR (Technical Qualification Review) where the readiness of the test facility to perform a test campaign with a test specimen is checked and confirmed.

The test campaign itself starts with the integration of the ULPM into the test facility P5.2. As this is a very exciting moment, starting very early in the morning (still dark outside) and ends very late in the evening (already dark outside), it is recorded very thoroughly, see Fig. 11.

Afterwards the ULPM needs to be connected with all I/F onto the test bench under specific and controlled conditions, e.g. continuous purging to prevent humidity into propellant lines.

More than 80 fluid I/F need to be connected by flexible hoses. Before connection the cleanliness of all test bench I/F and flexible hoses have been thoroughly verified on-site. The expected functional static and dynamic behavior has been verified by simulation during the early design phase and double checked after definition of the manufacturing details by the supplier. After attachment of the flexibles, Helium tightness checks have been performed and, where necessary, insulation material was attached.

The correct connection of the electrical interfaces (about 350 analog-input, 100 digital output, 90 digital input signals are exchanged between the ULPM and the test facility) has been verified with the complete signal chain with active stage elements, the so-called "End-to-End" tests, meaning valves are operated, sensors physically excited, whenever possible.

Fig. 11: ULPM integration into P5.2 test facility (© ESA)

5. Main challenges/results and first lessons learnt

Three main categories of challenges are to be treated by the operation team of the test facility: (1) Technical topics with respect to compatibility of the bench with the test specimen (ULPM) for hot-fire tests and other operations (2) Technical topic related to the preparation of the hot-fire tests and defined/repetitive operations (automatic sequences, instrumentation) and (3) organizational topics. Further elements are shown in Fig. 12.

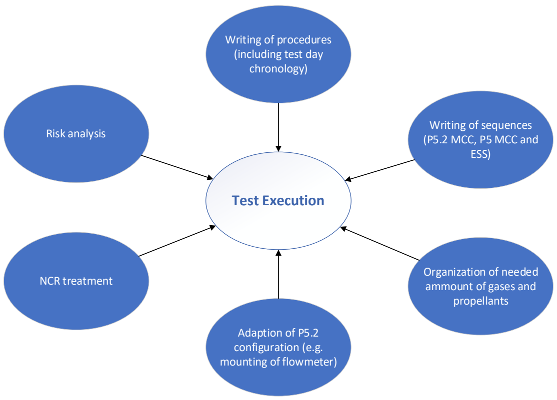

Fig. 12: Main elements for test execution during a hot-fire campaign

(1) Even as the test facility was designed and build on basis of the defined requirements of the Ariane 6 upper stage module, some evolution in stage design can result in smaller, yet relevant, incompatibilities of the test facility. Such incompatibilities have been identified and corrected, usually by adaption of bench configuration parameters or, in some cases, by hardware modifications of the test bench. The confirmation of conformance is done by a challenging step-by-step verification of every requirement versus bench performance parameter.

(2) The conversion of electrical signals from the sensors into physical values is done online during performance of a test with the upper stage, this allows a definition of the thresholds of the supervising majority logics also in physical values. The conversion is defined in the sensor database that contains all parameters for an accurate conversion. Baseline for the configuration of the measurement database are the calibration data of each sensor. The test requestor compiles these data in the so-called measurement request, where also the requested acquisition rates, filter settings and acquisition start/stop time stamps are defined. Implementation of these data into the configuration file of the individual test is done either by manual input or automated data import followed by a reliable verification process. The sequential execution of all automated process steps during a test day are defined by the test requestor in the so-called test request. Any manual process step that might be defined in the test request, is transferred into the test day chronology (a written document) by the operation team of the test facility. For example, the number of sub-programs for execution of the automated process steps by the measurement command control system of the P5.2 for a recent test with the upper stage at P5.2 was about 600, containing about 50.000 lines of code. Also, the redundant computer system is to be adapted for execution of the correct shut-down activities. The structure of input gathered from the test requestor (the customer of DLR) is shown in Fig. 13. Fig. 14 is a simplified view on the complex structure of the command systems used for execution of a hot fire test with the ULPM at P5.2.

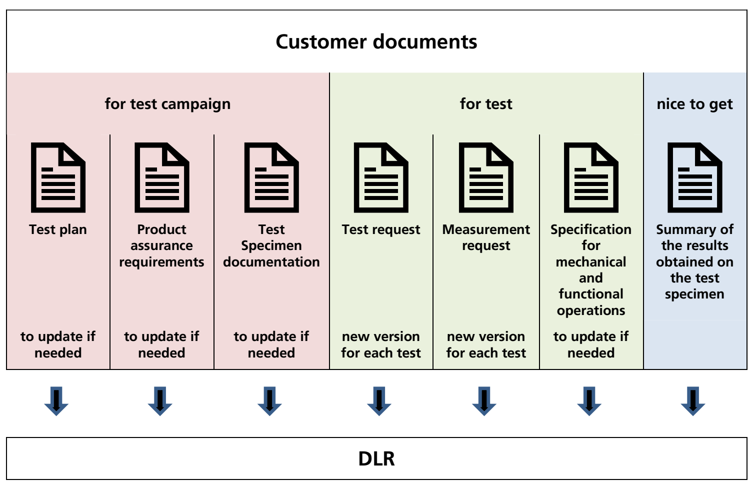

Fig. 13: Technical documentation or input from customer for a hot-fire test campaign

(3) The test organization distinguished safety considerations and technical considerations. The important safety considerations are the definition of safety parameters, definition of the personnel/people evacuation plan, definition of safety/evacuation procedures and assignment of personnel (firefighting team, ambulance, etc.) as well as analysis of the weather forecast. Main technical consideration are the task assignment and work shift plan for the test team (DLR and ArianeGroup) inside and outside the control room, establishment of the test day chronology, supervision of the refilling concept for securing media supply on the test day (Liquid Oxygen, liquid and gaseous Hydrogen, liquid and gaseous Nitrogen, Helium, Propane, cooling water, emergency generator fuel, several batches of media for all kind of supporting systems), and not to forget: preparation of relaxation zones in the control building and catering, this because the schedule of test activities might add up to 24h with no possibility of personnel to leave the control building for most of the time. For fast and deep analysis of events and their possible consequence during a test day, DLR as well as the test customer install experts in back-offices outside the safety perimeter with emergency communication hotline to the test leader. For details of the organization of the test team see Fig. 15.

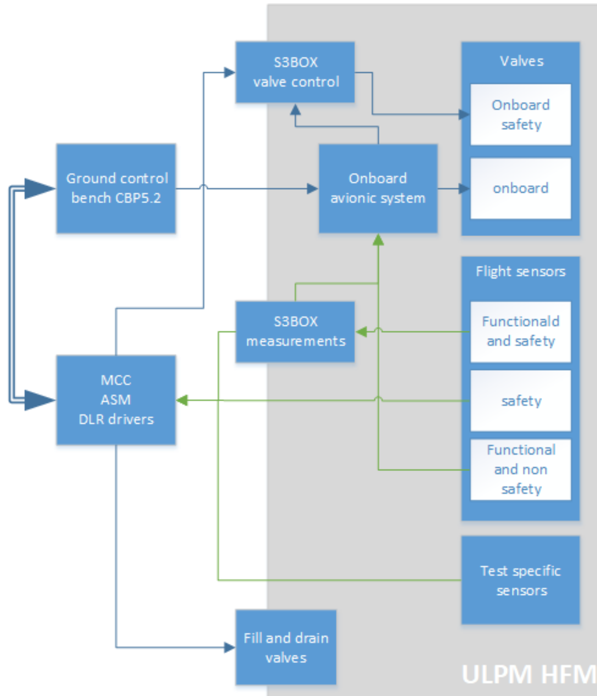

Fig. 14: Simplified command and control overview

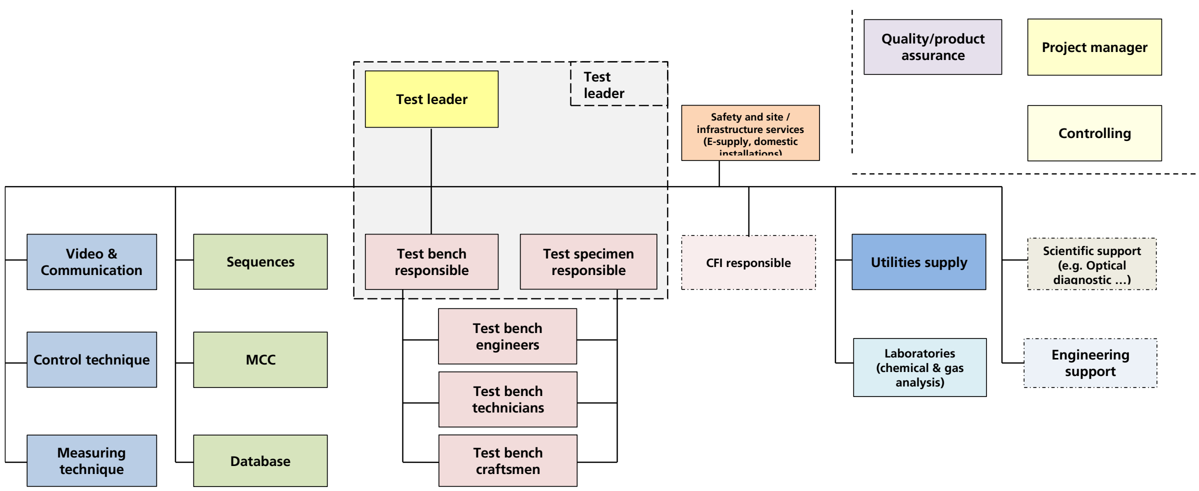

Fig. 15: DLR standard organization of a test campaign on an ESA facility at DLR Lampoldshausen

However challenging, at the end, when everything is implemented, integrated, modified, configured, checked and double checked and when the team is organized, the test day with engine hot-run operation can be initiated. In reality, such test day starts at 4am with manual preparation activities of the test bench and associated facilities as well as the initiation of the obligatory security precautions. After chill-down of the propellant supply lines of the bench the stage tank filling process starts around noon. Usual time of engine ignition is sufficiently before tea time, around 3-4pm.

Engine chill-down and Vinci hot-run is performed under control of the ULPM onboard computer (Fig. 16). For this purpose, the MCC of the test facility hands over the access of active elements to the ULPM computer, yet remains active to receive said control back in case of problems for immediate shutdown and securing stage and bench systems. After conclusion of all engine functions and another chill-down of the bench propellant lines the remaining LH2 and LOX is drained from the stage and the preparation of stage and bench reconditioning starts. In parallel, the relevant signal acquisition archives are secured and prepared for transfer to the customer. Depending on the set of requested test objectives, a tests day ends between 12pm and 4am.

Fig. 16: Test Facility P5.2 during hot-run with ULPM/Vinci® engine

6. Summary

The paper presents an overview on the complex technical and organizational structure of the ESA upper stage test facility P5.2 at the test center of DLR in Lampoldshausen, Germany, which has been designed for testing the ULPM (upper stage) of the new European commercial Ariane 6 launcher. After 5 years design and realization period first tests of the ULPM have been performed with hot operation of every propulsion element, showing impressive accordance with the expected and precalculated results, for the behavior of the test bench systems, thus providing the foundation of the formal R3 acceptance of this immense investment of the European Space Agency.

However, a lessons learnt process has been initiative from the very beginning of this first test campaign at P5.2 with the main goal to optimize the test day chronology and the applicable procedures as well as the allocation of expert's tasks during test preparation and test execution. The conclusive lessons learnt exercise will be done after the technical conclusion of the test campaign.

References

List of references

Reference to a conference/congress paper:

[1] P. Lutz, M. Kaufmann, A. Haberzettl, M. Mueller, M. Graser, D. Brugger, COSIE – COupling System for Integration of Engine, 3rd Ground-Based Space Facilities symposium, Marseille, France, 2022, 6 – 8 December.

[2] S. Dietershagen, A. de Zorzi, O. Condaminet, J.-M. Fouere, V. de Korver, A. Frank, K. Froehlke, D. Leiss, Ariane 6 Upper Liquid Propulsive Module Qualification, IAC-22-F1.2.3, 73th International Astronautical Congress, Paris, France, 2022, 18 – 22 September.