Institute of Space Propulsion
Institut für Raumfahrtantriebe

Status Report 2011
Preamble

In the course of the last five decades, the site in Lampoldshausen has played an integral part in the European space flight program. Together with its partners in the aerospace industry; the European Space Agency, national agencies, research organisations and universities, the team in Lampoldshausen makes an essential contribution to the development of European rocket propulsion systems and assures the continuous success of European operational launchers. A very close co-operation exists since 1959 with the major French organisations involved in space propulsion and the Ariane programs. This co-operation is vital to the success of current and future European launcher development projects.

Lampoldshausen has been the main German development and testing site for all European liquid fuel rocket engines ranging from attitude control engines (> 0.5 N) and apogee engines (>200 N) to large liquid hydrogen main stage engines (>1300 KN) such as Ariane’s main stage engine - the Vulcain 2.

At present and in the near future Lampoldshausen is dedicated to supporting Europe’s Ariane 5 ME program: the development of the new upper stage with the 180 kN, re-ignitatable engine Vinci. This engine is tested on the P4 test bed. High-altitude testing represents a major core competence in Lampoldshausen.

DLR Lampoldshausen is home of the Institute of Space Propulsion, one of the most important space research facilities. Management of the site was integrated into the Institute in October 2008, which comprises six key departments: Test Facilities, Engineering, Rocket Propulsion, Propellants, Technology and Safety & Quality.

In view of the fact that potentially hazardous facilities are operated on the site, safety management plays a key role in the Institute. A safety office, site security unit, site fire brigade, and medical service ensure the safety and protection of employees, facilities, and the environment alike during research and testing operations. The Safety & Quality department is responsible for acquiring operating licences from the relevant authorities and maintaining infrastructure on the site. A well-organised infrastructure of assembly halls, workshops, pump stations, sewage treatment plant, oxygen and hydrogen tanks, petrol station, and vehicle garages ensures smooth, trouble-free operation. The use of a variety of fuels and oxidisers means that special storage, handling and transportation facilities are a pre-requisite on the site.

The space company EADS Astrium also has a division on the premises. A number of other companies and institutes also make use of the site's services and test benches, thus contributing to a close-knit and beneficial alliance. These include the European Space Agency (ESA), the French space agency Centre National d’Études et de Recherches Spatiales (CNES), and the Société Nationale d’Études et de Constructions de Moteurs d’Aviation (Snecma).

In recent years, DLR Lampoldshausen has developed into a modern service provider now covering all stages of the testing process from the provision of test benches and the operation of engines to the recording and transmission of measurement data to the client.

With its engineering and operations departments on the one hand and the research departments on the other hand the Institute is a unique place which delivers results from the early stages of a development project all the way to qualification of the final product: a certified rocket engine.

The German Space Strategy, published on 1st December 2010, emphasizes that Lampoldshausen is the pillar which supports Germany’s efforts to guarantee access to space with the Ariane launcher family. Lampoldshausen’s unique high altitude facilities ensure that Germany’s duties within the European Launcher Community, namely systems responsibility for the old and new Ariane upper stages, will be fulfilled.

All critical components and operating procedures for the new upper stage engine, which goes by the name of Vinci, will be developed and tested in Lampoldshausen. In line with the German Space Strategy, DLR has defined specific research and development targets ranging from system analysis of the engines, thrust chambers, nozzles, combustion, fuel management, ignition - particularly under vacuum conditions, cryotechnology, all the way to testing, verification and validation and thus qualification of the rocket engines on the different test benches under settings characteristic of those found during launch and space flight.

It is well known that over the next few decades all launch vehicles will use chemical rocket engines. The key technology is combustion, and it is well understood in the scientific community that the
control and management of the exceptionally high power densities in rocket combustors is of peak importance. The governing equations which are used to model the multiple complex interacting processes in combustion chambers are highly non-linear and therefore extremely difficult to solve. While the application of computational fluid dynamics CFD and other improved modelling techniques in areas of compressor and turbine development paved the way to keeping expensive testing at a minimum, the control of combustion phenomena is still based purely on empiricism. Combustion modelling is currently only used to support the understanding of combustion chamber phenomena, like heat transfer or combustion instabilities, but up to now only semi-empirical methods have been used to design components like injectors, swirlers or the complete layout of a combustion chamber. The only possibility to tune the chemical combustion process is still solely by extensive testing in an environment of total quality control. This still holds for component tests on single injector elements as well as complete rocket engines with power head and nozzle. The Institute of Space Propulsion guarantees the maintenance of an infrastructure to develop and meet the requirements of today’s and tomorrow’s rocket engines.

All of Lampoldshausen’s research and development programs directly support European rocket engine development programs.

In addition to the unique features of high altitude testing and cryogenic technology for the qualification and development of space propulsion systems, DLR Lampoldshausen develops and manages the application of storable and gel propellants. The Institute co-ordinates the scientific and technical activities of the German Gel Technology Program.

The training of space engineers and scientists plays a major role in ensuring reliable, long lasting support of European engine development programs. Since 2005 DLR Lampoldshausen has addressed this with the DLR_School_Lab, a laboratory for young people where promising young scientists conduct experiments under the guidance of experienced scientists and engineers. As a next step the DLR Campus Lampoldshausen will be established to ensure the education and training also of bachelor, master and Ph.D. students with the aim of developing the DLR_Campus Lampoldshausen into one of the main sources of qualified personnel for the German space industry.

The Technology Transfer Centre (TTZ), a conglomerate of different regional business associations and DLR Lampoldshausen, works to improve networking among regional companies that are active in the field of science and industry. Clear synergies in the fields of environment, health and safety, combustion, ignition, fuel management, cryo-technology and systems engineering exist and present opportunities for partnerships within and outside of the space propulsion business.

The DLR Institute for Space Propulsion in Lampoldshausen draws on competence and experience to deliver qualified test results to national and European decision makers to support the DLR mission:

Knowledge for Tomorrow!

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Abbreviations

Institute of Space Propulsion
1. Research and Technology

DLR Lampoldshausen focuses on research and development testing with activities within the ARTA (ARIANE 5 Launcher Research and Technology Accompaniment) program which aims at phasing intermediate technical upgrades into the running ARIANE program. Hence, the activities of the Institute of Space Propulsion in Lampoldshausen are focused towards preparation of future launcher technologies.

Key issues in liquid propellant rocket engine technology are injector design, mastering of heat transfer and cooling in order to be capable to predict the cyclic life of thrust chamber components. The above mentioned components and features of a regeneratively cooled combustion chamber are illustrated in Figure 1.1.

![Figure 1.1: Sketch of an axial section of a regeneratively cooled combustion chamber.](image)

1.1 Engine Cycle Analysis

The development or enhancement of currently existing liquid rocket engines requires the precise knowledge of engine parameters. The latter determine not only the conditions under which single engine components must work but also determine whether a given engine can satisfy the requirements set by an envisaged application.

It is in this frame that engine cycle analysis plays a critical role in the estimation of the steady-state performance of future engines and in the detailed analysis of currently existing engines. Of course, system analysis is always used to analyse performance benefits of new component technologies.

Reliable software and extensive know-how become precious assets as they are necessary in order to perform qualified parameter and trade-off studies.

![Figure 1.2: Specific Impulse for Various Propellant Combinations for a 10kN Pressure-fed Engine](image)

An example of such a study is Kocher which examined ten different propellant combinations (Fig. 1.2), including both LOX-based as well as 90%H2O2-based combinations, for a liquid upper stage 10 kN engine. A trade-off analysis between pressure fed and electric-pump fed engine cycles was performed. Due to weight constraints and to the relatively short burn duration of merely 240 seconds, a pressure-fed solution with a combustion chamber of 20 bar and an expansion ratio of 180 was selected.

For each propellant combination a stage mixture ratio was selected based on a trade-off between the engine’s specific impulse and the volumetric specific impulse of the stage, as shown in Figure 1.3.
1.2 Propellants

The research and the development of technologies for the suitable application of novel energetic materials and the enlargement of the actual application ranges of common energetic materials for rocket, satellite and ramjet propulsion systems are the major fields of work. The work on common and advanced propellants covers both civil and security oriented applications. The main part of the activities is actually focused on gelled propellants and ionic liquids based propellants. Within the scope of the activities also properties of materials and components mainly with regard to their applicability in thrust chambers, storage devices and feeding systems are investigated and determined.

Gel Propulsion

Gel propellants have attracted attention for future rocket and ramjet propulsion devices, because they offer the possibility to build throttleable engines with easy handling and storage capabilities. Due to the non-newtonian flow behaviour of gels, a gel rocket motor combines major advantages of a solid rocket motor and a liquid rocket motor. Also for airbreathing ramjets the application of gel fuels is advantageous because of higher safety aspects in comparison to liquid fuels.

Common positive features of all kinds of gel rocket motors are primarily:

- Controllable thrust, either by throttling or by intermittent operation
- Low plume signature if no or only very small amounts of solid metallic fuel or inert particles are added
- Capability to increase the energy content of the propellants by adding e.g. metal particles without the tendency that the particles form sediments in the tank
- Avoiding of fuel slosh in tanks, which can be a problem for liquid rocket motors.

It could be shown within the scope of the German Gel Technology Program that the biggest advantage of a gel rocket motor is the potential to combine

- A superior degree of insensitivity
- Easy handling, transport and storage regulations
- Environmental friendliness of the used propellant and the produced exhaust gas.

Figure 1.3: Normalised Specific Impulse, Normalised Volumetric Specific Impulse, and Normalised Optimisation Function for LOX/LH2

The results of the study represent a catalogue of available options ranging from lower performance but storability, to higher performance but higher handling effort requirements.

In the following sections a number of new engine component technologies will be presented which are currently object of investigation at the Institute of Space Propulsion. The investigations themselves concentrate mostly on the behaviour of the fluid flow and on the technical aspects but only superficially on the advantages or disadvantages of such new technologies in terms of engine performance. These latter aspects are examined in dedicated system analysis studies.

There are a multitude of current technology development projects which require system analysis trade-off studies. These studies range from small technologies such as ignition systems to complete engine systems for future European launcher applications. A non-exhaustive list includes: staged combustion parallel vs. serial cycle analysis for the future European high thrust engine (HTE) and of course detailed expander cycle architecture analysis for upper stage applications such as the VINCI engine.

These two examples underline the importance of engine cycle analysis which brings system and component know-how together and thus increases the value of investigations performed at the Institute of Space Propulsion.

1.2.1 Propellants
The research and technology development activities on gel propulsion of the DLR Institute of Space Propulsion are mainly part of the “German Gel Technology Program”, where DLR also coordinates the scientific/technical activities, and the DLR-internal program “Advanced Missile Technologies”.

The present status report gives only a very short overview about some important results, which were obtained within the last years. The presentation covers on the one hand the technology preparative work in the fields of rheology, flow behavior, spray properties and combustion characteristics within basic experimental setups. On the other hand extensive work was conducted for the combustor process development with gel propellants up to distinct conditions relevant to the engine demonstrator within the German Gel Technology Program, which was developed by Bayern-Chemie. Detailed information, however, is given in a large number of publications and reports. The most important non-classified publications are given in the publication list of the institute. (see attached CD)

**Rheological Properties and Flow Behavior**

Gelled propellants are non-Newtonian fluids. They behave in the tank at rest like solids. Under sufficiently high applied shear forces, however, they can be fed through pipes due to their shear-thinning behavior. They can be liquefied to a large extent upon injection into the combustion chamber by the very high shear rates acting on the flow through suitable injectors.

Fig. 1.5 shows as a typical example the dependence of the shear viscosity upon the shear rate for a JetA-1(kerosene)/ThixatrolST gel in the upper diagram. The shear viscosity decreases with increasing shear rate up to a minimum and constant value \( \eta_\infty \), which is called upper Newtonian plateau. This plateau is often located near the viscosity of the basic fluid to be gelled. Thus it is obvious that with sufficient high shear rates in the range up to \( 10^2 \) or \( 10^4 \) s\(^{-1} \), which can be produced with distinct injector types, a sufficient liquefaction for flow and spray processes can be reached.

\[
\eta = \frac{\tau_0}{\gamma} + \eta_\infty
\]

For the characterization of the flow behavior of gel fluids in tubes of constant diameter as well as for the characterization of the spray behavior a generalized Reynolds number Regen, HBE is derived.

![Figure 1.4: Examples of gelled fuels](image1)

![Figure 1.5: Dynamic shear viscosity vs. shear rate (top) and determination of the yield stress \( \tau_0 \) (down) for a JetA-1/ThixatrolST gel](image2)
The critical Reynolds number specifies the transition from laminar to turbulent flow behaviour. For non-Newtonian gel flows in tubes the dependence of the critical Reynolds number from the material properties is numerically determined. Fig. 1.6 shows the calculated values of \(Re_{fl,HBE}\) as a function of the exponential factor \(n\) in the HBE equation for a constant value of the pre-exponential factor \(K=10 \text{ Pa.s}^n\) and distinct values for the yield stress \(\tau\) and the Newtonian plateau viscosity \(\eta_n\). The thick solid line \(Re_{fl,HBE}\) represents the analytically determined results from Ryan and Johnson for a power-law fluid (i.e. the HBE equation without the terms with \(\tau\) and \(\eta_n\)). The distribution of the critical Reynolds number \(Re_{fl,HBE}\) (open circles) shows a maximum at medium exponential factors \(n\). For \(n=1\), for which the HBE fluid characteristics approach a Newtonian fluid, the well known value of 2300 is found. At low \(n\) a limiting value above the Newtonian value occurs for \(n \rightarrow 0\).

At low \(n\), however, the analytically determined critical Reynolds number of power-law fluids decreases significantly below the Newtonian value of 2300. This is due to the fact that the power-law does not consider the finite viscosity of a real gel in the very high shear rate range. This leads to physically unrealistic low viscosity values at high shear rates, which lead to those very low critical Reynolds numbers. The fact that the critical HBE Reynolds number does not fall below the Newtonian value of 2300 is physically more coherent since the gel structure can dissipate more energy than a Newtonian fluid.

**Technology Demonstrator “Combustor Process” (TD-B)**

At the M11 test bench complex a modular gel rocket test setup (TD-B) was developed and erected for the gel combustor process development activities. This facility can be equipped with different modular model combustors, injector heads, etc. to allow detailed work on handling, feeding, ignition and combustion of gelled propellants. A GOX/GH2 ignition torch can be attached to the mounted model combustor so that non-hypergolic propellants can also be ignited. The investigated gel propellants, which were developed by the Fraunhofer-Institute of Chemical Technology ICT for use within the TD-B, can also be produced on-site. For this task, a laboratory room with reinforced walls was erected, in which potentially explosive propellant gels are produced under remote control. The enhancement of these propellants regarding their rheological, spray and combustion properties is conducted in collaboration with the ICT and Bayern-Chemie.

For the test runs the gel propellants are stored in cartridges with a movable piston inside. With hydraulic driving units the gel propellants can be fed to the injector head by moving the piston and pushing the gel into the connection tubes.

Within the scope of the work on combustor process development the thrust modulation capability could be shown by varying the gel mass flow rates. Also operational ranges could be determined for the investigated propellants within the chosen experimental setup. Figure 1.7 shows as an example the working area for a combustor of a distinct size with a distinct feeding and injector system and a distinct gel propellant.
**Energetic Ionic Liquids**

Today ionic liquids are generally defined as those salts with melting points below 100 °C and whose melts are composed of discrete ions, but for propulsion applications also aqueous and other solutions of various energetic salts and other organic and inorganic compounds are included in the definition of (energetic) ionic liquids. Ionic propellant components generally have a low vapour pressure and consequently can form only low amounts of vapors of species, which are possibly classified as toxic. Thus their hazard potential and their acute toxicity/exposure ratio are strongly decreased in comparison to other storable propellants like hydrazine and its derivates. Not only the liquid state is interesting for propulsion applications but also gelled ionic liquids have advantages. In this case throttleability will be combined with good storability, easy handling characteristics and reduced human and environmental exposure.

Ionic oxidisers as for example ADN (ammonium dinitramide \([\text{NH}_4]^+\text{[N(NO_2)_2]}^-\)) or HAN (hydroxylammonium nitrate \([\text{NH}_3\text{OH}]^+\text{[NO_3]}^-\)) are of particular interest. Work on ADN based liquid and gelled propellants has been started in Lampoldshausen in 2009. The liquid ionic monopropellant FLP-106 has been developed by the Swedish research organisation FOI and is of interest among other things for satellite propulsion systems like attitude control thrusters. It is based on ADN and several liquid ingredients. Currently, DLR is preparing model thrust tests in collaboration with FOI and the Austrian Institute of Technology in the scope of the GRASP program, which is funded via FP7 by the European community.

ADN based gels are of interest both as monopropellants and as gelled oxidizers for bipropellant gel rockets. Fig. 1.8 shows typical shadowgraph images of the spray behaviour of an optimized ADN based gel at high injection velocities. The original gel was developed within the scope of the German Gel Technology program by the Fraunhofer-ICT. The enhancement of the gel spray properties is a result of a successful collaboration between DLR, ICT and Bayern-Chemie. Furthermore a collaboration has been started in 2010 with the Fraunhofer-Institute of Technology for the investigation and development of novel energetic ionic liquids for propulsion applications.

**Figure 1.7:** Example of a working area of TD-B for distinct combustor size and propellant

**Figure 1.8:** Shadowgraph images of the spray behavior of an ADN-based gel making use of an impinging jet injector
Generalized Methods for the Performance Characterization of Satellite Propellants

Performance differences between propellants are usually assessed through the comparison of either the specific impulse $I_{sp}$ or the specific impulse density $I_{sp,d}$. However, each of these performance parameters could result in a different performance ranking of the propellants which makes it harder to make a suitable propellant choice (e.g. for developing green alternatives to the currently used storable propellants such as Hydrazine and Nitrogentetroxide) without having in mind an actual application. In order to overcome this problem, a unified performance assessment criterion for satellites based on both of the above mentioned usual performance parameters was developed at DLR Lampoldshausen. The validity of this unified performance assessment criterion has already been shown for a wide range of propellants (mono and bi-propellants) for a series of in-service satellites. In Fig. 1.9, the standard propellant performance criteria specific impulse $I_{sp}$ and density weighted specific impulse $I_{sp,d}$ are compared to the newly developed generalized specific impulse $I_{sp,generalized}$ for a series of monopropellants. The generalized specific impulse is defined as

$$I_{sp,generalized} = \alpha \cdot I_{sp} + (1 - \alpha) \cdot I_{sp,d}$$

Where $\alpha$ is an empirical factor with $\alpha = 0.92$ for bi-propellants and $\alpha = 0.96$ for mono-propellants.

![Comparison of the standard propellant performance criteria specific impulse $I_{sp}$ and density weighted specific impulse $I_{sp,d}$ to the newly developed generalized specific impulse $I_{sp,generalized}$ for a series of monopropellants.](image)

1.3 Propellant Injection

Propellant injectors are controlling by a major part the performance of rocket combustors. Independent of the engine cycle and application injection systems for liquid propellant engines share the following set of general requirements: acoustic and fluid mechanic decoupling of propellant supply system, propellant distribution dome and combustion chamber, homogeneous propellant distribution to individual injector elements to allow for optimal propellant distribution and mixing, controlled behavior during start-up transient to guarantee reliable ignition, flame anchoring and flame holding to ensure stable combustion, perform under steady state condition with minimum interference with combustion chamber wall at tolerable wall heat flux levels and, finally, achieve these goals with minimal pressure losses and maximum combustion efficiency.
Despite their functional importance the design of injectors is mainly based on empiric rules. Scaling with respect to the injected mass flow, temperature of the injected fluid, the injection of different fluids, or different combustion chamber pressures cannot be done in a reliable way, requiring extensive validation procedures and testing.

Research at the Institute of Space Propulsion has been focused up to now on shear coaxial injectors. Investigations are planned to be extended to impinging injectors in the frame of the DLR program FOLAN (Forschung für lagerfähige Antriebe / Research for storable propellants). The experimental research activities are addressing following aspects:

- Injection and atomization of propellants at supercritical pressure
- Effect of injector geometry and injection conditions on spray formation and flame stabilization
- Effect of the thermo-physical properties of the fuel on the atomization process for coaxial injectors.

Application dependent, there are a few more requirements such as efficient and stable operation at variable thrust levels for boosters, shift in mixture ratio and thrust for upper stage engines optimization and extreme throttling capabilities for landing missions. In line with the current ESA-program, these types of engine applications and injection system requirements will be in the focus of the upcoming years.

**Injection Systems**

Within the last decade the main emphasis of injection system technologies laid on research towards identification and quantification of dominating physical processes during transient start-up, ignition and steady state operation of rocket engines. Of specific interest was the impact of thermodynamic boundary conditions such as sub- near- and supercritical pressure and temperatures of the propellants on atomization and mixing, spray and flame angle, flame and combustor response. Aside the classical propellant combination of LOX/GH2, similar research has been performed for the propellant pair, LOX/CH4.

Key open questions to investigate were the differences in the behaviour of the liquid oxygen in terms of impact on atomization, ignition, flame and spray structure and flame dynamics when surrounded by either hydrogen or methane. Detailed thermodynamic characterisation of the fluids of those two propellant pairs is the basis of a proper injector design. While O2/CH4 (Fig. 1.11) shows clear signs of a type 11a system (bounded liquid-vapour equilibrium), O2/H2 (Fig. 1.10) behaves like a typical type 1b one (unbounded liquid-vapour equilibrium) and as a result in a O2/H2 system oxygen droplets exist at pressures which exceed by far its critical pressure of pure oxygen while in a O2/CH4 system no liquid oxygen exists above a reduced pressure value of 0.935. Obviously, such differences will have an impact on atomization, mixing and combustion at pressures relevant to liquid propellant rocket engines and thus as well on injector design.

![Figure 1.10: Two-Phase Diagram of the O2/H2 propellant pair.](image)

![Figure 1.11: Two-Phase Diagram of the O2/CH4 propellant pair.](image)
It has long been known that LOX post recess and LOX post taper angle are key factors for atomization, mixing and flame holding as shown in Fig. 1.12 where OH emission images of the near injector region of the single injector model combustor C are shown for a pressure of 60 bar, without recess (left) and with a recess of 0.67 LOX jet diameter (right).

![Figure 1.12: OH emission image of near injector region, left without recess, right with a recess of 0.67 d.](image)

Additionally, it has been shown experimentally that the diameter of the LOX post tube has at least for the propellant pair LOX/CH4 a non-negligible influence on flame anchoring and heat release.

Aside from classical shear coaxial injectors which are standard in cryogenic liquid propellant engines, a new injector concept has been looked at and developed, the API (Advanced Porous Injector). In comparison to all classical injectors which provide for proper atomization and by an appropriate propellant injection of the propellants, this concept bases entirely on atomization and mixing driven by combustion processes inside the thrust chamber - thus allowing for reduced pressure losses within the injection system. Up to now the concept has been validated for LOX/H2 at different thrust levels, mixture ratios and combustion chamber pressures (H2 supercritical at 50K).

Rocket engine applications such as booster or upper stage engine differ in propellant mass flow rate, combustion chamber pressure and thrust level. One of the most challenging requirements as far as the propellant injection system is concerned is the thrust variation requirement while maintaining maximum combustion performance.

The design of the API injector with the intrinsic destabilization and mixing mechanism is very well suited for such varying propellant injection conditions. The basic features of the API concept are a porous face plate through which all the gaseous hydrogen is guided to the combustion chamber and the integrated tubes for the liquid oxygen is shown in Fig. 1.13.

The central tube in Fig. 1.13 is the flame tube of the ignition system.

![Figure 1.13: API injector concept](image)

Fig. 1.14, below, shows the liquid propellant for three different mass flow rates. This figure was produced in one of many experiments that have revealed the injection characteristics of the API.

![Figure 1.14: Flow visualization of API concept for 3 different mass flow rates: left to right, 1.8 kg/s, 1.3 kg/s, 0.7 kg/s.](image)

The section height shown in this figure corresponds to roughly 1.5 combustion chamber diameters, a length where usually more than 50% of the liquid oxygen is consumed. The operating condition with maximum mass flow rate shows a minimum of surface irregularities.

An example of the performance of the API concept under realistic thrust variation conditions for two different hydrogen injection temperatures is shown in Fig. 1.15.

![Figure 1.15: Example performance of the API concept under realistic thrust variation conditions for two different hydrogen injection temperatures.](image)
Due to the throttling experiment that has been performed, starting at high pressures and continuously reducing the mass flow rates, the graphs show slightly decreasing efficiencies with increasing thrust levels. However, this effect is entirely due to the amount of propellant which is stored in the volume of the supply lines at higher pressure and which is released into the combustion chamber in addition to the propellant coming from the supply tank. The steady state values are marked at 37.5 and 128% throttling and reveal rather constant efficiency. The picture for 50K hydrogen however shows a decrease of the combustion efficiency of roughly 2 at lower thrust levels. It is worthwhile noticing that in contrast to classical shear coax injectors, stable combustion was achieved throughout all tested throttling levels.

### Gel Injection

For the production of sufficiently small gel droplets impinging jet injectors are useful because the necessary high shear rates are produced in the injector passages and in the region around the impingement point so that the gels can largely be liquefied. Detailed investigations were conducted with the doublet like-on-like type, whereas the characteristic working behavior like spray pattern and droplet diameters were determined in dependence of various parameters like gel composition, jet velocity, etc. The left set of shadowgraph images of Fig. 1.16 shows a typical example at moderate jet velocities of a kerosene based gel. The two images from perpendicular viewing directions show the atomization of the fluid to small droplets.

Detailed investigations of the spray and combustion behavior of gels with metal particle addition were also conducted. The results show that for smaller particles the influence of the particle diameter on droplet diameters does not seem to be very pronounced. Nevertheless particle diameters should be significantly below the injector diameter because of the danger of blockage.

It has to be mentioned that not every gel can be sprayed to small droplets. Several gels show a completely different breakup process, where fibers or threads are formed, which do not further decay. An example is presented in the right set of shadowgraph images of Fig. 1.16. It was shown in a recent investigation with various non-Newtonian fluids that elasticity seems to have an influence on hindering droplets formation and these gels behave as viscoelastic fluids. Further investigations are ongoing to get a better understanding of the occurring phenomena.

Detailed investigations on the spray behaviour with various Newtonian fluids were conducted. With the results a regime diagram with Weber and Reynolds numbers as parameters was created for a doublet like-on-like impinging jet injector, see Fig. 1.17. The different breakup regimes can be located here. It is evident that for droplet forming gels similar breakup patterns are obtained at high jet velocities like for Newtonian liquids.
Atomization at Supercritical Pressure

High thrust engines are operated at pressures above the critical pressure of oxygen ($p_c = 50$ bar). At these pressures oxygen can neither be described as a liquid nor as an ideal gas.

The injection of fluids at supercritical pressures is studied in cold flow experiments using liquid nitrogen as a substitute fluid for LOX at the M51-cryoinjector test bench. Flow visualization demonstrated the qualitatively different physics of the atomization process for liquids exhibiting a finite value of the surface tension and fluids at supercritical pressure (Fig. 1.18). Raman-scattering has been applied to obtain quantitative data on supercritical jet disintegration. This data is still used today by various research groups to validate numerical simulations tools as for example LES codes.

Ongoing interest in the research on supercritical atomization is driven by the further need for qualified experimental data to validate models and CFD tools. A specific focus is on the behaviour of binary mixtures near the critical point of one of the components.

Figure 1.17: Regime diagram for Newtonian fluids

Figure 1.18: LN2 free jet at (A) sub- and (B) supercritical pressure

In hot fire tests at representative conditions the effect of pressure on combustion efficiency, combustion roughness, and flame stabilization is analyzed with specific attention to whether conditions are sub- or supercritical with respect to the critical pressure of oxygen.
The focus of present activities is on advanced injection concepts (API), the effect of injector-wall interaction and the detailed investigation of the progress of combustion in the axial combustion chamber direction.

Spray Formation and Flame Stabilization

It was in the 1990’s that mounting of quartz windows to high pressure model combustors for the first time enabled optical access to the combustion chamber volume. The potential of qualitative and quantitative optical diagnostic methods has been investigated. Today Schlieren visualizations of the propellant injection process, imaging the emission of the OH-radical and CARS (coherent anti-Stokes Raman scattering) are validated tools for the investigation of spray formation and combustion in high pressure research combustion chambers.

The effect of the thermo-physical properties of fuel on propellant and combustion has been investigated in parametric studies on the M3.1 test bench. Injection conditions have been varied systematically and the reactive liquid oxygen sprays have been investigated for hydrogen and methane as fuels. The experiments clearly demonstrated the essential effect of fluid properties on the atomization and flame stabilization process (Fig. 1.19). Spray pattern and flame phenomenology vary significantly between LOX/GH2 and LOX/GCH4-flames for similar injection conditions in terms of Weber-number We and momentum flux ratio J.

Figure 1.19: Flame and spray pattern at similar injection conditions for hydrogen (left) and methane (right)

Upper stage engines are ignited and re-ignited at high altitude conditions. The bench M3.1 provides the ability to perform ignition tests at vacuum with cryogenic propellants. In these tests flash evaporation of the injected LOX has been observed, significantly influencing the spray pattern during the transient ignition phases. The spray formation and subsequent evaporation largely affects a major part of the process of ignition and subsequent flame stabilization. The phenomenon of flash evaporation at high altitude LOX-injection will be investigated systematically in the frame of the DFG SFB Transregio 75.

In view of the fact that hypergolic propulsion is seen as a national key competence the DLR Institute of Space Propulsion is aiming to broaden its competence to cover impinging injectors as well. In cooperation with the German industrial partner EADS the effect of injector design, fluid properties and injection conditions will be investigated with substitute fluids and original propellants. This work will be performed in the frame of the DLR research project FOLAN (Forschung für lagerfähige Antriebe).

1.4 Start Transients and Ignition

Anomalies in the past, such as the Aestus anomaly of Ariane 5G flight 142, have clearly demonstrated the need of mastering the ignition transient. Transient phases, such as start-up, shutdown, and throttling, need to be dedicated special attention, both experimentally as well as numerically. During start-up and shutdown, purging and draining of the liquid rocket engine volumes may lead to undesirable peak pressure and temperature values.

To master the start-up of different engine systems therefore means to understand and master not only the changes that the fluids undergo during the priming process but also to master the dynamic processes of each engine component and to master the coupling between the various components. Keeping all of this in mind, a suitable start-up sequence can be obtained which allows the smooth ignition of an engine.

Current and past experimental and numerical efforts are divided into transient flow investigations and in ignition investigations. The former aims at understanding the behaviour of fluids under transient conditions, such as upon rapid opening or closing of a valve, or upon injection into a combustion chamber in which vacuum exists. The latter examines ignition for both conventional as well as new propellant combinations and ignition systems.

Transient Flows

In the frame of a DLR research initiative FOS (Forschungsverbund Oberstufe, Upper Stage Research Network), which aims at consolidating upper-stage know-how, a dedicated test bench, the M3.5, is currently built which will allow the extensive investigation of water hammer effects with cryogenic fluids.

Initial investigations are concentrating on water as a reference fluid. Due to the easier handling of water when compared to cryogenic media a parameter...
variation of the main governing variable is also foreseen.

In a second phase, the test bench will be modified to allow the testing of liquid nitrogen and subsequently liquid oxygen. Other phenomena which will be investigated are friction and heat transfer under both transient as well as two-phase flow conditions.

The aim of these experimental investigations is to create a well-documented database which is so far missing for cryogenic fluids. This database is dedicated to validate and improve currently available two-phase flow transient models. The goal is to increase the prediction ability of the numerical tools which are used to simulate the transient phases in liquid rocket engine pipelines, regenerative cooling circuits and injection domes and elements.

Water tests conducted at the M3.5 test bench are of significant importance for the better understanding of phenomena observed in engines (RCS and OMS) using storable propellants. These activities are contributing to the DLR program FOLAN.

In parallel to the experimental investigations the Institute of Space Propulsion is performing transient flow simulation with numerical methods. Programs which are currently being used and continuously developed and which examine a rocket engine system or test bench fluid circuit in its entirety are mostly based on lumped parameter models. In such models a system is divided into sections along which the system parameters are considered to be uniform over its volume and then discretised into lumps. This allows the simplification of the partial differential equations into ordinary differential equations which in turn makes it possible to reduce the numerical complexity of the problem which needs to be solved. Although such models allow the analysis of system frequencies their accuracy is given by the assumptions on which the models’ underlying simplifications are based.

In the simulation of two-phase flow for example, a number of different approaches is possible. The first and perhaps most simple approach is the assumption of a homogenous two-phase flow. The Lockhart-Martinelli correlations are often implemented due to their simplicity and despite the latter good accuracy for a mostly uniform two-phase flow, e.g. priming of injection domes, for other applications such as cavitation, the implementation of these correlations lead to unsatisfactory results and discrete vapour cavity models are generally preferred.

In the frame of the FOS project numerical simulations using both commercial as well as in-house lumped parameter models are foreseen. The aim is to examine currently used models and assess their accuracy for a range of different two-phase flow conditions for both cryogenic and non-cryogenic fluids and to improve these models as is deemed necessary. The improvements undertaken will be performed as a trade-off between increased model accuracy, applicability and required computational time.

**Ignition**

The results of such investigations create the base for a better understanding of fluid flow conditions prior to ignition and therefore a better understanding of ignition itself. A windowed micro-combustor (Fig.1.20) equipped with a modular injection head is used to perform extensive optical diagnostics. A significant number of ignition experiments have been conducted in the past with a wide range of aims.

![Image: Figure 1.20: M3.1 Windowed Micro-Combustor](image)

In the EU Lapcat I project the investigation of methane as alternative fuel was undertaken. Using the windowed micro-combustor and a single coaxial injector element, ignition and combustion of both GOX/GCH4 as well as LOX/GCH4 for near-stoichiometric conditions was tested. The former made use of laser ignition by which a single laser pulse, which is coupled into the combustion chamber and locally creates plasma, is the only ignition energy source. The data obtained from the test campaign established a solid database for the numerical simulation of GOX/GCH4 ignition and combustion processes. During an extensive second test campaign, a torch ignition was used to ignite a coaxial jet of LOX/GCH4. Using OH imaging shadowgraphy and CARS, extensive diagnostics was performed both in terms of flame development, flame anchoring as well as flame temperatures. The
current EU Lapcat II project foresees testing of LOX/GCH4 for fuel rich conditions for applications in gas generators.

In the ESA Green Propellants project, three unconventional propellant combinations were tested: LOX/C3H8, LOX/C3H6 and LOX/Flamal. The aims of the investigations were to examine the quality of the ignition, i.e. to evaluate the ignition based on its smoothness, reproducibility and reliability, for an assessment of the applicability of such propellants in future non-hypergolic green-propellant engines. Both a single as well as a penta injector head were tested. Ignition was performed using a fuel-rich GOX/GH2 torch igniter. Nominal chamber pressures were in the range 6-7 bar with mass flows ranging between ca. 100 and 450 g/s for mixture ratios between 1 and 10.

Despite the fact that both the oxidiser as well as the fuel were in their liquid state, all ignitions were smooth, meaning without pressure peaks, and with a minimal delay. This was achieved by inverting the velocity ratio, $V_R$, of the injected propellants (Fig. 1.21), so that the oxygen injection velocity exceeds the fuel injection velocity. Usually the velocity ratio is greater than 1 (Vulcain 2, $V_R \sim 10$).

![Figure 1.21: Green Propellants: Velocity Ratio](image)

The campaign proved to be extremely successful and lessons learned included the handling of propellants which exhibit significant Joule-Thomson effects. Indeed due to the latter a two-phase flow was encountered which increased the complexity of the campaign significantly.

Current RCS technology is a well established and mature technology based on either a monopropellant and a catalyst or a hypergolic bipropellant combination to provide thrust. The implementation of these propellants on, for example, a cryogenic upper stage, calls for a separate propellant feed system and thus extra weight. Efficient RCS engines which would make use of the same cryogenic propellants as the stage engine provide a weight-saving potential. An ignition system capable of re-ignition would be necessary. Each re-ignition would have to be 100% reliable and reproducible.

Igniter technologies have seen an increased interest in the past decades due to the increasing re-ignition needs, such as for the upper stage Vinci engine. Weight reduction and redundancy considerations have led to an increased number of studies in alternative igniters technologies to the conventional pyrotechnical or spark plug igniters in use today. Such technologies include concepts such as resonance igniters, catalyst igniters and laser igniters.

Some preliminary examination of resonant ignition has been conducted at DLR but a much more significant effort has been invested into laser ignition investigations.

When compared to classical ignition methods, both in the automotive industry, i.e. spark ignition, and in the space industry, i.e. pyrotechnic/torch ignition, laser ignition system (LIS) offer multiple advantages. A non-exhaustive list includes:

- **There is no need for premixing**
- **There is no need for ignition system propellant valves**
- **A precise firing sequence can be defined**
- **Ignition of multiple rocket chambers is possible simultaneously**
- **It is applicable to RCS, large-scale rocket combustion chambers, future engine applications, such as RBCC, and is most certainly applicable to automotive motors (internal combustion engines)**
- **Low ignition delay times are possible**
- **Electromagnetic interference (EMI) is well below permissible levels for space flight.**

Studies conducted in the past at DLR examined the ignition process under vacuum conditions using laser ignition. The results obtained (Fig. 1.22) widened the already existing know-how as the significantly different initial pressure conditions lead to a drastically different behaviour of the injected fluids (wider spreading angles, flashing, etc.) and thus of the interaction between the injected fluids and incoming laser pulse. Parameter variations both in terms of injection parameters such as momentum...
flux ratio, J, Weber number, We (for liquid-gas combinations) or velocity ratio, V, (for gas-gas combinations), as well as in terms of initial pressure conditions (in the range 25 mbar to 1 bar), have been performed.

![Image](image1.png)

Figure 1.22: Shadowgraph Images of Flames Ignited under Vacuum Conditions

With the aim of increasing scientific knowledge about laser ignition as well as providing a preliminary assessment as to whether laser ignition is a potential ignition technology for RCS engines using oxygen as oxidiser and hydrogen or methane as fuel, DLR, as ESA contractor, is currently investigating into laser ignition for RCS applications in a technology readiness program: Cryogenic RCS Thruster Technology - Laser Ignition.

A breadboard thruster (Fig. 1.23) consisting of a contoured windowed combustion chamber with relevant contraction ratios and a RCS-relevant chamber contour was designed and manufactured. A single coaxial element injector head, which allows the injection of the propellants under relevant J numbers, was also constructed.

![Image](image2.png)

Figure 1.23: Cryogenic RCS Thruster Technology - Laser Ignition: Windowed Contoured Breadboard Thruster

The project is now in the testing preparation phase. The test plan foresees testing with both a table-top Nd:YAG laser with 532 nm and a miniaturised Nd:YAG laser with 1064 nm. Parameters that will be varied during the test campaign are not only the laser wavelength and propellant combination but also the focus location, and laser energy.

1.5 Combustion and Stability

Combustion instability is still a frightening phenomena for development engineers despite the progress that has been made in basic understanding of the combustion processes in rocket combustors development of analytical and numerical design tools and decades of acquired empirical knowledge. Combustion instabilities are well known to the European launcher community: combustion instabilities in the storable propellant engines Viking and Aestus as well as in the cryogenic upper stage HM7B have resulted in the inability to reach the target orbit or even in the loss of the mission.

The ongoing need for a better understanding of combustion instabilities, has motivated the progress in experimental technologies and the computational resources available today to address the phenomenon of high frequency combustion instabilities by basic research at the Institute of Space Propulsion. The focus is on experimental work with the key objective to resolve the interactions mechanisms by which energy from the combustion process is transferred into the acoustic energy of the excited mode. Other subjects addressed are the performance of passive damping devices and low-order modelling of acoustic absorber behavior.

DLR is cooperating on the subject of combustion instabilities in the frame of a MoU with German and French partners from industry, research institutions and agencies (Astrium, CERFACS, CNES, CNRS, ONERA, SNECMA, Technical University of Munich). The Rocket Engine Stability Research Initiative (REST) is regularly organizing scientific and numerical modelling workshops.

Interaction of Acoustics and Combustion

Common Research Chamber (CRC)

The CRC is a small scale experimental setup (Fig. 1.24) operated at the test bench M3.3 for the investigation of the interaction of an acoustic wave with combustion. The chamber diameter is 200 mm, due to this dimension the acoustic frequency of the first tangential mode is at about 4 kHz, a value representative for eigenmodes of upper stage
engines. The combustor has optical access to the complete combustion volume. Thus high-speed visualization methods can be applied with a temporal resolution high enough to resolve the acoustical time scales. Two injection systems are analyzed. A shear coaxial injector is used for the liquid oxygen as the oxidizer and either hydrogen or methane as a fuel. The capabilities of the M3.3 test bench allow the injection of hydrogen at a temperature of ~100 K, methane at ~280 K. Investigations with two liquid propellants are also possible. Liquid oxygen and ethanol are injected with like-on-like injectors. The maximum chamber pressure is 10 bar.

A key technique in the experiments is the acoustic excitation of the combustion volume by a siren, which opens and closes a secondary nozzle periodically with an area of about 10% of the main nozzle. Burning cryogenic sprays can thus be studied under forced acoustic excitation. The orientation of the excited mode is varied by mounting the secondary nozzle at various circumferential positions. Depending on the mounting position of the siren, the burning spray is exposed to an acoustic velocity anti-node or a pressure anti-node.

The acoustics of the CRC and the generation of noise by the combustion process itself have been characterized in tests without the siren. By extensive variations of the injection conditions it has been found for LOX/GH2 as well as for LOX/GCH4 it is the Weber-number, the ratio between aerodynamic and surface tension forces, has a dominant effect on the spontaneous pressure fluctuations. However, the studies also show propellant specific differences between hydrogen and methane.

In order to enable the spatially resolved evaluation of flame response to acoustics numerical tools have been developed to reconstrcut the acoustic pressure field inside the combustor based on dynamic wall pressure measurements (see below). Applying these tools to the tests without forced excitation resolved that the spontaneous pressure fluctuations are composed of coherent acoustic waves. Although these waves have small amplitude, they show a well organized behavior. It was possible to identify the detailed evolution of the first tangential eigenmode (1T-mode), especially the transition between the standing mode and the spinning mode.

With forced excitation using the siren it could be shown, that the Weber-number controls the level of acoustic pressure, similar to the tests without excitation. No other parameter characterizing the injection conditions like momentum flux ratio, velocity ratio or propellant injection pressure drop showed a significant correlation with excited acoustic amplitudes.

With high speed visualization of the flame emission the fluctuation of the heat release could be determined during forced excitation. The amplitude of the fluctuation at the excitation frequency is taken as the heat release response to the acoustic field. From the phase shift between acoustic pressure and heat release fluctuation the time lag is determined, a key parameter needed as input for low-order models for stability rating. The 2D-information of the flame visualization allows addressing the spatial symmetry of the flame response. The comparison of this symmetry with the symmetries of the acoustic pressure or that of the acoustic velocity field is the key to the main objectives of the work: to clarify whether the coupling of acoustics and combustion is based on processes related to the acoustic pressure or the acoustic velocity. An example of an experimentally determined acoustic velocity field during excitation of the 1T-mode is shown in Fig. 1.25.

By using this data and analyzing the spatial distribution of the heat release the flame response to acoustic velocity could be determined as shown in Fig. 1.26. For LOX/GCH4 the experiments were able to prove, that the highest response is from the con-

![Figure 1.24: The Common Research Chamber (CRC) for high frequency combustion instability research.](image-url)
rical flame around the spray axis and that in this region the coupling is due to acoustic velocity. Contrary to this, data produced using LOX/GH2 propellants available today indicates pressure coupling.

To our knowledge these are the first published experimental results that deliver the spatially resolved flame response, a prerequisite to determine the coupling mechanism.

Figure 1.25: Experimentally determined acoustic velocity field in the CRC.

Figure 1.26: Spatial distribution of the heat release response of a burning LOX/GCH4 spray to acoustic excitation.

**Combustion Chamber H**

The operational range to investigate the interaction of combustion and acoustics is significantly extended by the combustor H, operated at the P8-test bench.

The focus of the objectives is on chamber acoustics. The rectangular cross section guarantees well defined standing transversal waves at representative frequencies. The eigenmodes of the acoustically coupled system of combustor H, injectors and propellant manifolds have been analyzed by numerical simulation in order to identify potential interaction of manifold resonances with the combustor (see Fig. 1.27).

Tests have been performed with hydrogen at ambient temperature and the flame response has been evaluated as a function of the injection conditions. A clear dependence of the flame response on the LOX-to-hydrogen velocity ratio and on the mixture ratio ROF is found. However, the dependencies do not reflect what was found in the work performed by NASA in the 1960’s. Further tests with hydrogen at 100 K and at 45 K are in preparation and will clarify whether these results can be explained by hardware specific effects or by therm-physical or fluid-dynamical arguments. Especially the application of high speed visualization techniques to resolve spatially and temporally the response of the LOX-spray and the response of the flame to the acoustic excitation is expected to contribute unique new data to the problem of combustion instability of LOX/GH2-flame at high pressure conditions.

Figure 1.27: Acoustic eigenmode of combustor H with a strong excitation of the hydrogen manifold.

**Combustion Chamber D**

Combustor D was originally designed for heat transfer measurements and is now used for combustion instability experiments as well. Operational conditions are similar to combustor H. However, the combustor provides two features that allow research complementary to combustor H. The combustor is equipped with a 42-injector head, thus favouring injector-injector interaction in a much
more effective way as with the penta-injector of chamber H. The cylindrical cross section enables the evolution of spinning modes, which are often regarded as the most dangerous in rocket applications. However to the circular cross section this combustor does not allow the mounting of windows for visualization techniques. For that reason a specific segment is in preparation to be equipped with dynamic pressure sensors and fibre optical probes to resolve the dynamic wall pressure distribution and flame emission simultaneously. By applying similar reconstruction techniques for the acoustic pressure field as in the CRC it is expected that a detailed insight into the evolution of unstable modes can be elaborated with this setup.

Absorber Physics

When the CRC has been operated with the siren a systematic deviation of the measured acoustic eigenfrequencies to that expected for a cylindrical resonator has been found. The expected 1T-mode was measured as a virtual doublet (Fig. 1.28). The two components have been labelled as 1T1 and 2T1, following a detailed numerical analysis of the mode symmetries. The underlying physics is that the inlet of the secondary nozzle exhaust forms an additional resonance volume to the combustor. The eigenspectrum of coupled resonance systems is different from the spectra of the individual systems. The solutions of the numerical modal analysis deliver not just resonance frequencies but at the same time the acoustic pressure and velocity fields in the chamber and the absorbers. The DLR-tools meanwhile also cover an analysis of these fields in order to evaluate the contribution of viscous and thermal dissipation to acoustic damping in the frame of a linear acoustic theory.

Gel Combustion

The combustion behavior of various gel fuels with and without metal particle addition was investigated in a pressurized combustion chamber under ramjet relevant conditions of the incoming air flow concerning pressure and temperature at test facility M11. The hot vitiated air flow is produced by H2/O2-burners. For example, it could be shown that for distinct kerosene based gels and for higher air temperatures self ignition occurs. This is advantageous, as in the case of a possible temporal air intake blockage or air mass flow reduction this self ignition behaviour would lead to a restart of a gel ramjet engine.
1.6 Heat Transfer and Cooling

Due to the extreme thermal loads rocket combustion chambers are always operated at the limit of today's material and cooling technology. The standard cooling technology in high thrust engine applications is regenerative cooling. A cooling fluid (usually cryogenic hydrogen) is fed through cooling channels in the combustor wall to keep the wall temperature at manageable levels. For very high heat loads additional film cooling is applied. An advanced concept investigated in the Institute of Space Propulsion is effusion cooling. For all cooling technologies an optimum design requires a precise knowledge of the heat transfer of the hydrodynamical losses of the cooling system. Despite the progress in numerical methods there is still need for qualified experimental data to verify models and to validate simulation tools. Essential data is obtained at representative conditions, specifically at pressures and heat flux levels near to rocket engine conditions. Heat transport phenomena are therefore in the focus of the scientific investigations in the department of Rocket Propulsion at DLR Lampoldshausen.

Regenerative Cooling

Regenerative cooling is the most widely used method of cooling a combustion chamber and is accomplished by flowing high-velocity coolant over the back side of the chamber hot gas wall to convectively cool the hot gas liner. The coolant with the heat input from cooling the liner is then discharged into the injector and utilized as a propellant. The best solution to date is the “channel wall” design, so named because the hot gas wall cooling is accomplished by flowing coolant through rectangular channels, which are machined into an inner liner fabricated from a high-conductivity material, i.e. oxygen-free copper or copper alloys such as Narloy-Z (CuAgZr). A sketch of a cross section of a regeneratively cooled combustion chamber with rectangular cooling channels is shown in Fig. 1.30.

Film Cooling Technology

Film cooling provides protection from excessive heat by introducing a thin film of coolant or propellant through orifices around the injector periphery or in the chamber wall near the injector or chamber throat region. This method is typically used in high heat flux regions and in combination with regenerative cooling. Sample engines where film cooling is applied are the SSME, F-1, J-2, RS-27, Vulcain 2, and the RD-171 and RD-180 with the latter two being the only ones where an additional cooling film is generated near the throat.

Measurement Methods

Due to the high temperature gradients associated with high heat fluxes precise heat transfer measurements pose demanding requirements not only for the measurement system but as well for the experimental techniques. Different measurement techniques have been adapted and applied to the specific conditions of rocket combustion.

Figure 1.30: Sketch of a cross section of a regeneratively cooled combustion chamber with rectangular cooling channels (size of channels exaggerated).
The standard calorimetric method measures the integral heat flux into the cooling fluid by determining the temperature difference between entrance and exit of the cooling channel.

In Fig. 1.31 model combustor B is shown which is segmented in axial direction. With this combustor the axial distribution of the hot gas side heat transfer is determined as a function of operational conditions and the effect of the injector element - wall interaction is assessed.

For heat transfer measurements with high spatial resolution the gradient or inverse method is applied. The test specimen is specifically designed to allow temperature measurements at well selected locations in the structure. These local structural temperatures are used to reconstruct the complete thermal field. Fitting parameters of numerical simulations, until best agreement between experimental and numerical data is achieved, delivers detailed information on the thermal-physical situation: local values of wall temperature distributions and local heat transfer coefficients. Detailed investigations on systematic measurement errors due to sensor technology and sensor mounting technology have been performed to maximize the measurement accuracy. The inverse method is applied to resolve the 2D-distribution on combustion chamber walls and to resolve thermal stratification effects in curved and high aspect ratio cooling channels.

Cooling Channel Side Heat Transfer
EH3C

Highest thermal loads are experienced in a combustion chamber in the nozzle throat. In the Vulcain 2 engine heat flux values can reach up to 80 MW/m². Due to the geometrical constraints in this region the cooling channels are curved and by wall friction and pressure gradient forces vortices are induced in the channel flow. These so called Dean vortices are expected to increase the heat transfer up to 30%.

The reliable prediction of the effect of the vortical flow on the heat transfer is addressed in a specific experimental setup, the Electrically Heated Curved Cooling Channel (EH3C) tested at the M3.2 test facility. To enable the investigation of thermal fluxes as high as 15 MW/m² at laboratory conditions the concept of the "thermal nozzle" has been developed and validated in the Institute of Space Propulsion. A copper test specimen with a converging cross section, collecting the energy of the heated base, allows the realization of high heat flux densities in asymmetrically heated cooling channels. Its thermal characteristics are near to a real regenerative cooled chamber wall.

Two specimens are available for heat transfer investigations. One specimen allows measurements in a straight cooling channel, a second specimen is used for the analysis of a curved cooling channel. Heat flux is imposed by a controllable and stabilized electrical power supply providing up to 25 kW electrical power. In Fig. 1.32 the specimen with the curved cooling channel is shown. More than 100 thermocouples in the cooling channel walls deliver the structural temperatures needed to resolve the axis and the height of the cooling channel. Various cooling fluids (hydrogen, methane, nitrogen) and for calibration purposes also water can be tested at flow conditions with Reynolds numbers up to $5 \times 10^5$.

The measurements provide quantitative data for the validation of models and simulation tools.

Part of the activities using the EH3C setup is performed in the frame of contractual work, especially to gain knowledge with liquid methane as cooling fluid.
**EHT**

The heat transfer investigations with cryogenic fluids are currently extended to storable propellants. Motivation is the development of a storable propellant demonstrator engine in Europe. Based on the EH3C concept an Electrically Heated Tube (EHT) setup is derived. The work is performed in a contractual frame with EADS Astrium. The heat transfer of N2O4 is of specific interest.

**HARCC**

The effect of thermal stratification in High Aspect Ratio Cooling Channels (HARCC) is investigated with a specifically designed combustion chamber at the P8 test bench. The liner segment of 200mm length is regeneratively cooled with LH2. Around the circumference of the combustor cooling channels are milled with different aspect ratios (see Fig. 1.31), grouped in four 90°-sectors. The mass flows in each sector are determined independently and in each sector the temperature increase of the cooling fluid is determined. The temperature field in the chamber wall is measured at several axial locations. The concept of the HARCC experiment allows the simultaneous investigation of 4 different cooling channels geometries, thus assuring same test conditions for each geometry.

Data from the HARCC experiment are used to validate low-order in-house models, like 1D-models or a more sophisticated quasi-2D-model. The HARCC experiment will provide one of the dedicated test cases to be used to validate the DLR TAU code for rocket combustion chamber applications.

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**Hot Gas Side Heat Transfer**

Staged combustion cycle engines are investigated in the frame of demonstrator programs in Europe to prepare the development of a high performance engine for the next generation launcher. Film cooling will potentially be needed to manage the heat loads in the preburner or to support regenerative cooling in the main combustion chamber to assure reliability.

A gaseous or liquid fluid can be injected parallel to the chamber wall in order to produce a protecting low temperature layer on the chamber wall. In the DLR model combustor E, H2 is injected as cooling film on the periphery of the injector face plate (Fig. 1.34 and Fig. 1.35). The measurement segment is instrumented to enable the measurement of the tangential and axial variation of the heat flux, i.e. the cooling film efficiency. Applying the inverse method delivers data that are used to validate 3D heat-transfer models. One focus is the investigation of the interaction of the streamlines downstream the injectors near the wall and their effect on the local heat flux distribution (Fig. 1.36).

Film cooling efficiencies are investigated for various cooling fluids, specifically hydrogen and methane.

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![Figure 1.33: Cross section of the regeneratively cooled liner segment of the model combustor “D”.](image1)

![Figure 1.34: Model combustor E with full instrumentation for film-cooling experiments at test bench P8.](image2)

![Figure 1.35: Injection head of the model combustor E with H2-injection for film cooling of the liner segment.](image3)
Heat Transfer in Supersonic Flow Conditions

The capabilities for heat transfer investigations at the Institute of Space Propulsion are currently extended to regenerative cooling and film cooling in nozzles. A specific test article, the DIN-nozzle, has been designed and manufactured (Fig. 1.37). Tests with model combustor E on the P8-bench provide data on the cooling film behaviour in a supersonic flow and heat transfer in the cooling channels with their specific curved geometry due to the nozzle contour.

Figure 1.36: Tangential distribution of the heat flux mapping the injector/wall effect in model combustor E.

Figure 1.37: DIN-nozzle for investigation of film cooling in accelerated, supersonic flow.

1.7 Lifetime Assessment

The cyclic thermal and structural loading of chamber wall structures leads for core stage engines like Vulcain to cyclic plastic strains of about 2%. In order to obtain accurate prediction results, the following effects have to be taken into account:

- Temperature dependency of the elasto-plastic material parameters
- Combination of isotropic and kinematic hardening
- Short term viscoplastic effects, leading to a stiffening of the material for high loading speed
- Long term viscoplastic effects, leading to a creep deformation of the structure
- Transient thermal loading of the structure.
Cyclic Failure Analyses of Regeneratively Cooled Structures

Based on the results of the structural analysis of the chamber wall structure, the number of cycles to failure has to be analyzed. Standard post processing life time assessment methods take into account the LCF damage of the material only. In order to increase the accuracy of the life time estimation, DLR extended the standard post processing life time assessment model by taking into account the ratcheting damage as well as the thermal degradation, leading to a decrease of the ultimate strain of the material.

Optimization of Geometric Parameters of Regeneratively Cooled Structures

Once a coupled analysis method is available for a regeneratively cooled structure (containing a fluid flow analysis of the coolant as well as a thermal, a structural and a life time assessment analysis of the wall structure), it is possible to use mathematical optimization methods in order to obtain an improved design, i.e. more cycles to failure than in the initial design. The used optimization methods can handle both, design variable constraints as well as optimization result constraints – allowing for taking into account technological limits for the dimensions of the cooling channels as well as cooling system limits such as the pressure loss in the cooling channels. Different optimization methods were compared at the institute: a conjugate Gradient method as well as a gradient free method. Exemplary optimization results are given in Fig. 1.39.

Modelling of the Cooling System

Component Production Process

When thermally based methods like welding or brazing are used for the connection of different parts of a cooled structure, then considerable thermal strain induced deformations may occur. One way of assessing such deformations is to measure them after the production process. However, numerical analyses of thermal connection methods allow for a prediction of production induced deformations of newly designed structures in an early development phase already. Therefore, a methodology for performing numerical welding analyses was developed at DLR Lampoldshausen. In Fig. 1.40, the thermal field in a 2D cross section of a 3D model during a Finite Element analysis of the welding of Vulcain II tubes is shown.
Modelling of Hydrogen Embrittlement

Hydrogen embrittlement is a hydrogen induced material degradation, leading to a softening of the plastic behavior as well as to a decrease of the ultimate strain of the material. As a first step, stationary hydrogen embrittlement is considered. Under this assumption, the local hydrogen concentration is only dependent on:

- The external hydrogen pressure
- The temperature
- The local stress
- The local plastic straining.

Once the hydrogen concentration is determined, its influence on both the Low Cycle Fatigue (LCF) as well as on the High Cycle Fatigue (HCF) behavior of wall structures is considered.

For LCF analyses, the softening of the plastic behavior of the material is taken into account locally for all elements of the Finite Element model in each sub step of the non-linear analysis. An extended strain based Wöhler approach is used, where the number of cycles to failure is not only dependent on the cyclic strain level, but also on the hydrogen concentration.

For HFC analyses, an elastic behavior of the material can be assumed. Therefore, the hydrogen embrittlement is taken into account by a post processing method. Again, an extended (but this time stress based) Wöhler approach is used, where the number of cycles to failure is not only dependent on the cyclic stress level, but also on the hydrogen concentration.

**Material Characterization**

In order to provide suitable input parameters for the numerical analyses mentioned in sections above, material tests and the determination of material parameters from these test results are necessary.

Tensile and LCF test samples are widely used for this purpose. A Finite Element coupled Least square fit method developed at DLR RA (“inverse Finite Element Method”) uses test data from a hydrogen embrittlement test set-up as indicated in Fig. 1.41 for the determination of the parameters describing the plastic deformation of chamber wall materials.

The result of the tests shown in Fig. 1.41 is a relationship of the pressure applied from the bottom of the test set-up and the resulting deflection of the tested thin disk. The advantages of such tests are:

- Excellent test result repeatability
- Loading speeds up to 200 % per second
- Similar thickness of the test specimen in comparison to chamber wall structures.

Finite Element analyses of the thin disk and the clamping tool as shown in Fig. 1.42 allow for an inverse determination of the plastic parameters of the tested material.

**Validation of Numerical Analyses**

The extreme loading of the materials used for the production of rocket combustion chamber wall structures such as:

- Temperatures up to 900 K for copper basis alloy structures
- Heat fluxes of up to 80 MW/m²
- Thermal gradients up to 200 K/mm
Cyclic straining up to 2% in a single cycle often exceed the standard range of the numerical methods used for the analysis of chamber wall structures such as CFD methods for the analysis of the coolant flow in the cooling channels, as well as structural and cyclic fatigue analysis of the chamber wall structure. Therefore, a validation of these numerical methods is essential when they are supposed to support designs of new hot gas wall structures.

Test results of model, sub scale or full scale combustion chambers are used for this purpose.

Table 1.1: Validation possibilities for numerical analyses of thermally loaded wall structures.

<table>
<thead>
<tr>
<th>analysis type</th>
<th>physical parameter</th>
<th>measurement device</th>
</tr>
</thead>
<tbody>
<tr>
<td>coupled CFD analysis of the coolant flow and thermal analysis of the wall structure</td>
<td>coolant pressure</td>
<td>pressure sensor(s)</td>
</tr>
<tr>
<td></td>
<td>coolant temperature</td>
<td>thermo-couple(s)</td>
</tr>
<tr>
<td></td>
<td>coolant mass flow rate</td>
<td>mass flow meter(s)</td>
</tr>
<tr>
<td></td>
<td>temperature inside the structure</td>
<td>thermo-couple(s)</td>
</tr>
<tr>
<td>structural analysis of the wall structure</td>
<td>deformation</td>
<td>perthometer or 3D capable microscope</td>
</tr>
<tr>
<td>life time analysis of the wall structure</td>
<td>counting the number of loading cycles until the structure fails</td>
<td></td>
</tr>
</tbody>
</table>

Although the measurements given in Table 1.1 seem to deliver considerable validation data, some restrictions exist for combustion chamber measurements.

**Chamber Heat Flux Measurement Restriction**

The direct determination of the heat flux into the thermally loaded side of a combustion chamber is difficult:

- Measuring the heat flux by measuring the heating of the coolant delivers an integral value only (that means no local distribution) and might lead to high measurement errors in case the temperature increase of the coolant is small.

- Measuring the heat flux by means of temperature measurements in different radial positions of the chamber wall might for high heat fluxes lead to high measurement errors due to possible positioning inaccuracies of the thermocouples.

- Measuring the heat flux by means of heat flux sensors might lead to high measurement errors due to insufficient contact of the heat flux sensor(s) with the remaining structure.

**Hot Gas Side Chamber Wall Temperature Measurement Restriction**

During hot run tests with combustion chambers, only point wise temperature measurements by means of thermocouples are possible.

**Deformation Measurement Time and Component Restriction**

For hot run tests with a combustion chamber, only the following restricted deformation measurements are possible:

- Out-of-plane deformation measurement (deformation component measurement restriction)

- Measurements before and after - but not during - the hot run (deformation measurement time restriction).

In order to overcome the above mentioned measurement restrictions, a new test facility as described in section 5.12 was set up at DLR Lampoldshausen – allowing for tests of small combustion chamber wall cut-outs (so called TMF panels) by replacing the hot gas loading of the chamber by a laser loading. The (in comparison to chamber tests) unique measurement capabilities of this test facility and its validation capability are listed in Table 1.2.
Table 1.2: Unique measurement capabilities and validation possibilities of TMF tests (which are not possible for combustion chamber tests).

<table>
<thead>
<tr>
<th>analysis type</th>
<th>physical parameter</th>
<th>measurement device</th>
</tr>
</thead>
<tbody>
<tr>
<td>coupled CFD analysis of the coolant flow and thermal analysis of the structure</td>
<td>heat flux through the thermally loaded surface of the structure</td>
<td>total laser beam power</td>
</tr>
<tr>
<td>structural analysis</td>
<td>absorption of the surface of the TMF panel at the panel test temperature</td>
<td>combination of thermocouples and a high precision pyrometer with spectral range equal to the laser wavelength</td>
</tr>
<tr>
<td></td>
<td>2D temperature field</td>
<td>infra red camera</td>
</tr>
<tr>
<td></td>
<td>2D, 3 component deformation field ((u_x, u_y, u_z)) during the cold flow and the hot run</td>
<td>stereo camera system (requires speckle marks on the surface of the TMF panel)</td>
</tr>
</tbody>
</table>

Exemplary Validation Test Specimen

A validation test specimen as shown in Fig. 1.43 was produced and provided to DLR by its industrial partner ASTRIUM.

This specimen can be considered as a 5-channel cut-out of a much larger thermally loaded full scale structure with coolant inlet and outlet connections at both ends. The original material (a nickel basis alloy) was covered by a thin coating (visible as green colour in Fig. 1.44) in order to increase the absorption of the optical heating device (a laser) as described in section 5.12. Both, the heat flux through the wall structure as well as its surface temperature can be separately controlled by a variation of the optical heating (laser) power and the mass flow rate through the cooling channels of the thermally loaded structure.

Measured Surface Temperature of the Thermally Loaded Structure

In Fig. 1.44, the measured 2D thermal field during a thermal loading of the validation test specimen is shown.

The temperature distribution is used for the validation of the coupled analyses (CFD for the coolant flow and Finite Element analyses of the heat conduction inside the thermally loaded wall structure).

Measured 2D Deformation Field of the Thermally Loaded Structure

In Fig. 1.45, the measured 2D out-of-plane deformation field during a thermal loading of the validation test specimen is shown.

The deformation field is used for the validation of Finite Element structural analysis methods and provides (together with the number of optical heating cycles to failure) the basis for the validation of methods for the analysis of the cyclic fatigue of thermally loaded wall structures.

Material Properties Testing

The tasks of the institute involve the investigation and determination of properties of materials and components mainly with regard to compatibility and abrasion. In actuality this is a small area and
work is mainly conducted in collaboration with other DLR-internal and external institutes and other research organizations.

For the test of erosion and high temperature stability of different materials with respect to combustor and nozzle relevant conditions a test facility was developed and erected at DLR Lampoldshausen test site. This facility is able to produce heavily particle and droplet laden hot gas flows with temperatures and area specific impulse densities of the condensed phase, similar to distinct smaller solid rocket motors. The hot abrasive jet wash is produced by the combustion of particles containing solid fuel tubes of e.g. HTPB (hydroxyl terminated polybutadiene) with a preheated and oxygen enriched air flow in a primary and a subsequent secondary combustion chamber. A sketch of the Abrasive Hot Gas Test Facility (HotGaF) is presented in Fig. 1.46 and an image is given in Fig. 1.47. The C/C-SiC materials for the nozzle structure were developed by the DLR Institute of Structures and Design.

![Sketch of the Abrasive Hot Gas Test Facility (HotGaF) with a test specimen at a cross section in the expansion part of the nozzle](image1)

![HotGaF with C/C-SiC nozzle, metallic sample fixture and a C/C-SiC test specimen](image2)

The production of the oxygen enriched hot vitiated air flow is conducted by making use of hydrogen/oxygen burners. Due to the design of the HotGaF facility similar to a connected pipe ramjet combustor test facility the time period in which the abrasive jet wash attacks the samples can be varied by the quick shut-down of the “air” heater at pre-selected times and the opening of the bypass valve, which can also be seen in the sketch of Fig. 1.46. The test runs were conducted in an automatic operation mode by a SPS remote control system. The big advantage of this facility is that “load” pulses of pre-selected time can be generated and used for the determination of abrasion histories. The time history of the combustor pressure of a typical test run at an intermediate combustor pressure level can be seen in Fig. 1.48.
The enhancement of the HotGaF facility was funded by the Technology Marketing Department of the DLR. The development of the ceramic C/C-SiC nozzle structure is a collaboration between the DLR Institutes of Structures and Design (BK) and of Space Propulsion. C/C-SiC test specimen and jet vanes for the test phase are produced and delivered by BK. This program was successfully finished in late 2010.

The compatibility and durability of new and commonly used fuels and oxidizers with the materials used in tanks, valves, injectors, etc. are important for a safe and reliable operation of propulsion systems. Service times can last up to more than a decade as for example the attitude control systems of distinct satellites. Stress corrosion cracking (SCC) of e.g. titanium materials in nitrogen tetroxide or MMH or the swelling behaviour of plastic materials in hydrazine are only two examples, which need a detailed testing before such materials can be used. For this task several rooms of the physical-chemical laboratory are equipped for a safe testing of material probes under highly toxic and/or aggressive environmental conditions (e.g. MON, nitric acid, hydrazine, etc.). The analysis of the tested materials is done in-house or depending on the measurements to be conducted also in collaboration with other institutes and research organizations.

![Figure 1.48: Time history of combustor pressure of a typical test run at an intermediate combustor pressure](image)

![Figure 1.49: View from the rear end into the nozzle section during a test run](image)

![Figure 1.50: Test set-up for stress corrosion testing in nitrogen tetroxide containing oxidizers](image)
1.8 Combustion Chamber Technology

For technology development and basic research the test facilities at the Institute of Space Propulsion provide unique opportunities. An essential part of generating a database at near to representative conditions are appropriate test specimen. A series of model combustors and combustion chamber components have been designed at the Institute of Space Propulsion, each dedicated for the investigation of specific aspects of thrust chamber technology. The model combustors have chamber diameters ranging from 50 to 180 mm. At P8 thrust levels of up to 40 kN, representative to upper stage engines, are reached. The fact that these test specimens are operated at near representative conditions requires the application of design methodologies and manufacturing processes similar to real rocket engines. The important difference is that the model combustors can be specifically designed according to the requirements for instrumentation and diagnostics derived from the scientific test objectives. The operational conditions that can be assessed with the model combustors in terms of mixture ratio and chamber pressure are shown in Fig. 1.51. An overview about the available model combustors is given in the following.

Model Combustor B

Combustor B is composed of a series of segments, each individually fed by cooling water (Fig. 1.52). Thus the axial evolution of the heat flux can be investigated by the caloric method. This is especially of interest by characterizing different injection element designs. The combustor has a diameter of 50 mm.

The segmented design enables the integration of specific test segments dedicated for example for the investigation of thermal barrier coatings or effusion cooling technologies using ceramic materials.

In Fig. 1.52 combustor B is shown with a porous injector head (section 1.3) in order to validate the effect of injector/wall interaction on the heat transfer for the API-injection concept.

Model Combustor C

The Combustor C is equipped with windows protected by a cooling film from the hot combustion gases. Combustor C thus provides optical access to the combustion volume in the region near the injector face plate. LOX atomization can be investigated at supercritical pressure conditions under hot fire conditions. The flame stabilization mechanism and the progress of combustion are visualized (Fig. 1.53). The demonstrated capability to operate windowed combustors at pressures as high as 70 bar is also a prerequisite to apply laser based non intrusive diagnostics as for example CARS (section 1.11). Combustion chamber C is operated at P8 but can also be tested at the test bench P6.1. The chamber diameter is 50 mm.
Model Combustor D

Model Combustor D is dedicated to heat transfer measurements in regenerative cooling channels using LH2 as cooling fluid at the test bench P8. Thermal loads on the hot gas side as well as on the cooling channel side are representative to cryogenic engines, as for example the Ariane 5 upper stage engine HM7B or the expander cycle engine Vinci which is currently under development. Combustor D has a diameter of 80 mm and its segmented design allows a flexible configuration (Fig. 1.54).

The combustor is manufactured with a similar method of construction as flight engines: the liner is formed by an inner copper cylinder, in which the cooling channels are milled. The channels are closed by electro-deposition of copper. An outer galvanic nickel shell serves to withstand the structural loads.

A key component is the so called HARCC-segment (HARCC: high aspect ratio cooling channel). This segment is cooled by cooling channels with aspect ratios between 1.2 and 30. More than 80 thermocouples are implemented at various distances to the hot gas wall and provide temperature data used for the reconstruction of the thermal field and heat fluxes with the inverse method.

Combustor D is used in addition for basic research on the interaction of combustion and acoustics. Due to its large diameter of 80 mm as compared to the other model combustors tested on P8 the acoustic resonance frequencies are lower and the associated time constants are in a range where acoustics can couple to combustion chamber processes such as atomization and droplet evaporation. In these tests chamber D is regeneratively cooled using water as cooling fluid.

Figure 1.54: Model combustor D for the investigation of heat transfer in high aspect ratio cooling channels with LH2 as cooling fluid.

Model Combustor E

Model combustor E has water cooled segments and is equipped with temperature sensors to resolve the temperature field in the wall structure in axial and circumferential direction by applying the inverse method (Fig. 1.55).

Additionally at specific locations hot gas side wall temperatures are measured by flat mounted thermocouples. The chamber is thus suitable for the analysis of the hot gas side heat transfer. Another specific feature is the capability to rotate the instrumented liner relative to the injector head thus enabling measurements with tangential resolution of the heat flux along the chamber perimeter. The main objective for which chamber E is used, is the investigation of the film cooling efficiency. Experiments can be done at a maximum pressure of 150 bar, the chamber diameter is 50 mm.

Figure 1.55: Model combustor E for heat transfer measurements using the inverse method.

Model Combustor H

Combustor H is designed for the investigation of combustion instabilities at representative pressure conditions and at energy release densities typical for combustion chambers with multiple injection elements. A key feature of chamber H is the optical access to the region near to the faceplate. Thus high speed visualization methods can be applied to resolve the interaction of acoustics with the LOX disintegration and the combustion processes.

The cross sectional dimensions of the rectangular design result in transversal acoustic eigenmodes at frequencies near to 4 kHz, typical for flight engines. The chamber can be excited by forced excitation with a siren at specific frequencies (Fig. 1.56).

The chamber is operated at the P8 test bench. Investigations can thus be done using hydrogen at temperatures from ambient down to 45 K. One of the main objectives is to resolve the role of hydrogen temperature on the stability behaviour.
1.9 Nozzles

The nozzle is the part of the rocket engine that accelerates the hot combustion gases to high velocities. It is the key driver for a high specific impulse as it converts the thermal energy released in the combustion chamber to kinetic energy, resulting in thrust. It is the system part with the predominant interaction to ambient conditions and has to be carefully designed with respect to its specific operation profile.

In order to propel the different stages of a rocket, three main scenarios exist and require different nozzle designs:

- First stage or booster application
- Main stage application
- Upper stage application.

Beside the choice of the fuel combination, these applications differ in the operation profile. For example a main stage nozzle has to deal with decreasing ambient pressure with varying fluctuation levels during the ascent of the rocket. Size, length, area ratio and weight of the nozzle have to be optimized to obtain a maximum overall flight performance.

An important issue of nozzle design is the structural load being induced during transient start up of the engine and sea level operation. Possible flow separation inside the nozzle on ground leading to undesired side loads have to be avoided. Such flow structure interactions not only affect the nozzle itself but also the engine, the actuators, the rocket’s structure and the payload. Avoiding flow separation during ground operation leads to a limited nozzle length and area ratio, resulting in performance losses during the ascent of the rocket. These losses can be covered by applying innovative high altitude adaptive concepts like the dual bell nozzle.

Not only the complex after body flow field of an ascending rocket has to be regarded but also the interaction between the nozzle and flow fields of ground test facilities and launch pads. The nozzle is therefore another rocket engine system part that has to fulfill flight operation and ground testing requirements. Hence, nozzle technology development must consider rocket and test facility requirements.

Special regards have to be put on upper stage nozzles being operated in flight under vacuum (space) conditions but tested on ground in high altitude test facilities, where they interact with a complex system of a high altitude chamber, a recompressing diffuser and several ejector stages. Especially, the flow back wash of the facility during shut down has to be taken into account, an operational condition that never appears during a subsequent space mission operation.

Nozzle research therefore has to cover a wide field of activities. Studies were performed experimentally as well as numerically to increase the technological readiness level of nozzle innovations starting with cold flow tests on test facility P6.2 leading over to
hot flow tests on test facility P8 and in future on test facility P6.1. This includes the interaction of the nozzle and the test facility.

**Conventional Nozzles**

A key interest in the field of conventional first or main stage rocket nozzle applications is flow separation during the transient start up process, the increased wall heat flux within the flow separation zone and the induced side loads. For this reason a common test campaign was setup with the partners Astrium ST and Volvo Aero Corp. named CALO to study cooling aspects within separated hot nozzle flows on test facility P8. Three specimens with a truncated ideal contour nozzle were tested:

- CALO A, water cooled and calorimetric measured, as reference
- CALO B with a gaseous hydrogen cooled base nozzle following the new so called sandwich design and providing a Vulcain-2-like cooling film for the calorimetric nozzle extension
- CALO C also with the hydrogen cooled base nozzle but with a pure film cooled INCONEL nozzle extension skirt (Fig. 1.58).

The successful test campaign demonstrated the reliability of the sandwich design concept (later on tested in full scale on test facility P5 as NE-X) and a stable cooling film. Furthermore the influence of the cooling film on elongating the separation zone (73%) and leading to an increased heat load, was discovered. The detected asymmetric film distribution, leading to a reattached flow condition and a resulting side load peak, gave a direct insight in the transient Vulcain 2 start up process.

Cold flow subscale tests at test facility P6.2, either conducted under high altitude conditions within a chamber or under ambient conditions on a horizontal test rig, allow fundamental insights on nozzle flows. With these studies an advanced and simplified flow separation criteria as well as a separation length model were developed. Well known but hitherto unexplained side load peaks of nozzles operating under low nozzle pressure ratios were traced back to boundary layer relaminarization within the nozzle throat and a following asymmetrical laminar-turbulent transition causing a stable but partially reattached nozzle flow.

The first time application of pressure sensitive paint within a nozzle proved the ambient oxygen impact on nozzle boundary layers resulting in possible post combustion effects of hot flow applications. Internal developed non optical methods like back flow frosting (BFF) or the use of temperature sensitive paint yield information on vortex generation shortly downstream of the nozzle throat affecting the heat input (fig. 1.59).

Figure 1.58: Film cooled CALO C nozzle at test facility P8, prior to hot test

The successful test campaign demonstrated the reliability of the sandwich design concept (later on tested in full scale on test facility P5 as NE-X) and a stable cooling film. Furthermore the influence of the cooling film on elongating the separation zone (73%) and leading to an increased heat load, was discovered. The detected asymmetric film distribution, leading to a reattached flow condition and a resulting side load peak, gave a direct insight in the transient Vulcain 2 start up process.

A detailed cold flow subscale test campaign, where a nozzle was cut step by step, yields the correlation of nozzle flow pattern and maximum side loads during transient nozzle start up. As main driver the deflected exhaust jet shear layer was identified (Fig. 1.60 and Fig. 1.61). The results had been verified with hot flow subscale side load measurements obtained with CALO C nozzle.

Figure 1.59: BFF visualizes vortex structures shortly downstream of the nozzle throat

Figure 1.60: Deflected exhaust jet shear layer passing the nozzle exit plane causes maximum transient start up side loads
The excellent cold flow results were used within a common FSCD/ATAC CFD workshop organized by ESA as a test case and meanwhile are a standard reference worldwide for CFD flow separation validation.

A new approach was tested at test facility P8 with the Vulcain-2-like DIN nozzle (scale of 1:8.3) where the upstream regeneratively cooled nozzle part consists of milled cooling channels, as shown in fig. 1.63, and then closed by a galvanic nickel layer. The downstream part is formed by a radiative cooled skirt ($k_0 = 32$ to $57$). Based on a DLR patent the nozzle is manufactured from Inconel®600, preventing material stress and thus minimizing deformation during hot fire runs. It has been designed in the frame of the Advanced Altitude Simulation Programme (AAS).

The cooling fluid is dumped as a cooling film on the inner surface of the nozzle skirt. In experiments with the DIN-nozzle objectives related to heat transfer in supersonic accelerated boundary layers as well as side loads and flow separation are addressed. Tests are performed at pressures from 50 to 130 bar and mixture ratios ROF from 6 to 7.3.

Parts of the presented work were performed within the European Flow Separation Control Device (FSCD) group. The task of the group (with members like Astrium ST, CNES, DLR, ESA, LEA, ONERA, SNECMA and Volvo Aero Corp.) was to study the flow separation within rocket nozzles and to suggest a flow separation control device. As a common candidate the high altitude adaptive dual bell nozzle concept was identified.

**Altitude Adaptive Nozzles**

The innovative dual bell nozzle consists of a conventional base nozzle, a characteristic wall contour inflection and an attached nozzle extension featuring a constant wall pressure profile (Fig. 1.64). Due to stable flow separation on sea level, followed by an abrupt transition to full flowing high altitude operation during ascent of the rocket the dual bell offers a performance gain on ground as well as during ascent.
lated hysteresis characteristics enabling a stable and permanent high altitude operation. A new transition criteria was developed and a new flow state called sneak transition was detected.

Ongoing warm flow tests on test facility M11 focus on geometry and heat load of the wall inflection.

Parts of the presented dual bell work are performed within the frame of the collaborative research program SFB-TR40 of the Deutsche Forschungsgemeinschaft (DFG) as well as in TEKAN 2010, a national research initiative.

Figure 1.65: Vulcain-2-like film cooled hot flow dual bell demonstrator, adapted to DIN base nozzle, to be tested at P8

The future developments will focus on geometrical nozzle design and cooling variations (conventional or film layer). Also fuel combination, mass flow and ROF variations are of interest. A first step will be the demonstration of a film cooled Vulcain-2-like dual bell nozzle at test facility P8 (Fig. 1.65). Tests with dual bell nozzles adapted to the fuel combination LOX/GCH4 at test facility P6.1 will follow.

Upper Stage Nozzles

Also of interest are unconventional upper stage nozzle concepts like the expansion deflection (ED) nozzle in reverse flow configuration, where the combustion chamber is positioned inside the nozzle. This leads to a shorter upper stage and to increased heat pickup, an advantage which might be used for new expander cycle developments.

Figure 1.66: Planar ED nozzle at M11 with overlaid CFD calculation

A detailed test series was conducted on test facilities M11 and P6.2 using a planar ED nozzle where an elongated centre body simulates the combustion chamber in reverse flow configuration. The test specimen with removable side walls enables either optical access via glass windows or pressure measurements via an insertable pressure port matrix to study the flow field within the nozzle throat and downstream of the centre body wake. Pressure and temperature measurements along the centre line of the upper and lower nozzle wall complete the results.

Test Bench Interaction

The interaction of the nozzle and the test facility environment or the interaction within a high altitude simulation chamber in combination with a diffuser and an ejector stage is studied in P6.2. The fields of interests are transient start up side loads and fluctuations induced by the test setup. A side load reduction device is under development (Fig. 1.67). It decreases the side loads that are induced during the transient start up or a stable separated nozzle operation. This device will enable future rocket engine demonstrator tests that request a thrust level variation on a test facility like P5.

Figure 1.67: Test of pre-developed side load reduction device on test facility P6.2.
The combination of nozzle flow and test facility interaction is essential for safe rocket engine operation and ground testing. This knowledge consolidates the DLR experience in test facility operation and design.

Fluid structure interactions such as those caused by an ovalizing nozzle structure during ascent of a rocket and advanced cooling concepts will be important future topics.

1.10 Numerical Flow Simulation

Numerical flow simulation covers a wide field of applications, from cryogenic liquids to supersonic hot gases, and supports test specimen verification and test data evaluation.

Cooling Channels

The need of a short-response time in the engineering design process justifies the application of correlations or 1D-simulations for heat flux prediction. However, thermal stratification phenomena cannot be captured with these models. The quasi-2D-model (q2D) is an approach to detail the modelling in a sufficient depth without neglecting the relevant processes contributing to the heat transfer. Unlike the 1D-models the q2D-model takes into account the transport process in the axial direction of the cooling channel. However, perpendicular to the channel axis the transport of thermal energy is resolved with respect to thermal diffusion, whereas mass transport is neglected. The q2D-model has been implemented at the Institute of Space Propulsions and validated with data from the HARCC experiment. This model is now available as an engineering design tool with moderate requirements for computational power and a prediction ability superior to the 1D-tools.

3D-CFD-Simulation

CFD tools promise to capture the full geometrical complexity and fluid dynamics, however without validating the selected submodels the predictions of CFD tools have limited reliability. Results of CFD simulations depend strongly on chosen boundary conditions, turbulence models, turbulent transport properties, boundary layer treatment, real gas models and the effects of the computational mesh. As an example in Figure 1.68 the affect of the turbulence modelling on the predicted vortices in a curved cooling channel is shown.

As of today the commercial code CFX is the standard code used for heat transfer modelling at the Institute of Space Propulsion (Fig. 1.69). The DLR code TAU is currently tested with respect to CFX’s capabilities. Predictions of CFX as well as of Tau are compared to the experimental data obtained to clarify the adequate choice of submodels and parameters.

![Figure 1.68: Dean vortices in the curved cooling channel EH3C as predicted by CFX using different turbulence models.](image)

![Figure 1.69: 3D CFX pressure / streamlines computation demonstrate vorticity within a cross section of TMF panel.](image)
**Effusion Cooling**

Effusion cooling, where a small amount of cooling fluid is directly injected through a porous wall into the combustion chamber, avoids the fuel pressure losses within the cooling channels of conventional combustion chambers and offers an overall performance gain. To study the film stability and distribution a rectangular chamber segment with side windows and an attached planar convergent–divergent nozzle segment is in development. The design phase is supported by a CFD study and includes 3D effects, especially in corners.

![Cooling fluid injection through porous wall segments in planar test specimen](image)

Figure 1.70: Cooling fluid injection through porous wall segments in planar test specimen

Figure 1.70 shows a result obtained with the commercial tool Fluent. The tests are planned using nitrogen under ambient conditions as the main fluid and nitrogen of 150 K as cooling fluid injected through a porous wall, identifiable as the box on the upper left.

**Nozzle Flows**

The flow inside the supersonic part of an ovalized nozzle separates asymmetrically. An effect which in some cases leads to a nozzle collapse. Fig. 1.71 shows a 3D CFD study of an ovalized nozzle performed with the DLR code TAU.

![3D TAU calculation of an ovalized cold flow subscale nozzle](image)

Figure 1.71: 3D TAU calculation of an ovalized cold flow subscale nozzle

The accurate flow separation prediction in supersonic nozzles is still difficult. Here, DLR’s TAU code offers an advantage compared to commercial codes. An extreme application is the prediction of the flow pattern and the transition of dual bell nozzles. A comparison of experimental and numerical results provides a detailed insight of the flow pattern evolution around the wall inflection. Figure 1.72 compares the dual bell’s sea level and high altitude mode.

![2D TAU Mach number calculation of a cold flow subscale dual bell nozzle. Sea level mode (upper part) and high altitude mode (lower part)](image)

Figure 1.72: 2D TAU Mach number calculation of a cold flow subscale dual bell nozzle. Sea level mode (upper part) and high altitude mode (lower part)

**Operating Conditions in the Facilities**

Numerical simulations are also performed by the department of Engineering concerning the operational conditions of test facilities in combination with a test specimen or for risk assessment. One example is a study of the failure impact of the projected upper stage test facility P5.2 on the test facility P5. The pressure wave presented in figure 1.73 was simulated with FLACS (Flame Acceleration Simulator) in cooperation with the Fraunhofer Institute (EMI), the Karlsruhe Institute of Technology (KIT) and the GexCon in Norway (FLACS Program). The aim of the safety conditions study was to ensure that all possible constructions are verified with the latest modeling approaches.

![Calculation of pressure wave by stage failure](image)

Figure 1.73: Calculation of pressure wave by stage failure
**Pro-TAU Initiative**

The upcoming ProTAU project is a cooperation between the DLR Institute of Aerodynamics and Flow Technology / Department Spacecraft and the Institute of Space Propulsion. The aim of the project is the establishment of an independent DLR competence in modelling and simulation of rocket propulsion systems and the related components. The focus is on the validation and future development of the DLR in-house CFD code TAU. The Institute of Space Propulsion will provide high quality, detailed and state of the art experimental data as input for validation and future development of TAU and on the other hand benefit from this reliable tool for future design and simulation of propulsion systems by reducing the limitations of commercial tools.

Within the first project phase of three years it is foreseen to join and intensify current activities of both institutes. Four fields of activities are identified and integrated in the ProTAU project:

- Combustion chambers: High pressure liquid rocket engine injection, involving real gas thermodynamics and spray combustion. Unique test data from windowed combustion chambers for single injectors of sub- and supercritical fluids are available on a wide range of pressures.
- Nozzle extensions: Effects of static nozzle extension deformation on the separation behaviour and the expected side loads. The experiments will be designed and prepared with numerical support, thus the experimental results will satisfy the needs of clear boundary conditions and validation data.
- Test facilities: Several test cases are identified in order to compare commercial tools and experimental data with TAU results. The focus lasts from subscale cold flow test facilities to the hot firing upper stage engine VINCI under vacuum condition at the test facility P4.1. This will be a good performance test of the state of the art capability of TAU.
- Cooling channels: Advanced turbulence modelling considering the sand roughness for the prediction of pressure loss and heat transfer will be included in TAU. Test data for various cooling channels are available.

Experimental activities, including measurement technique developments, are foreseen at the Institute of Space Propulsion whereas the TAU development is taking place at the Institute of Aerodynamics and Flow Technology. The simulation and validation of TAU will take place at both institutes.

The first phase of the ProTAU project is the initiation of a long term cooperation in order to improve TAU and therefore strengthen the competence of DLR in analysing and evaluating launcher systems and their components.

### 1.11 Diagnostics

Optical diagnostic methods, successfully used at ambient conditions, cannot be applied to rocket combustor conditions without adaptation or even only after specific developments. Flow conditions in rocket combustors are characterized by pressures up to 150 bar and temperatures up to 3500 K. The mounting of windows to these combustors is needed for optical measurements and diagnostic objectives must be considered already during the design phase of a test specimen. Pressure gradients are much higher and thus the gradients of the refractive index in the flows. Spectroscopy of molecules has to take into account the effect of high temperature and especially the effect of high pressure on the population of the ro-vibrational states.
Diagnostic techniques adapted for model combus-
tors have meanwhile found their way to the large
scale facilities in Lampoldshausen. They are regular-
ly applied in development tests and technology
tests at the test facilities P3.2, P4, and P5.

**Visualization Techniques**

Schlieren optics and shadowgraphy are standard
methods and deliver basic information on flow
topologies and the distribution of liquid phase in
two-phase flows. These methods are mainly applied
for the visualization of atomization and mixing of
injectors and nozzle expansion plume diagnostics
(Fig. 1.75). Modern digital camera systems can
record images at frame rates up to several kHz. This
allows an essential extension of diagnostic capabil-
ties, as for example the study of phenomena during
the start up transient like propellant dome filling,
the propellant injection process or the flame evolu-
tion and stabilization after ignition (Fig. 1.76).

Schlieren optics and shadowgraphy rely on the
visualization of refractive index gradients. The real-
ization of a good contrast at high pressure condi-
tions requires experience in designing the optical
setup. Shadowgraphy has been applied at a maxi-
mum pressure of 180 bar, in the frame of work
contracted by SNECMA on pre-burner investiga-
tions.

**Particle Image Velocimetry (PIV)**

The development of customized PIV for supersonic
flows was the starting point in Lampoldshausen to
use PIV. Today a commercial PIV-system is in opera-
tion for the velocimetry of droplet sprays.

Image processing techniques used in PIV have been
adapted for thrust chamber displacement mea-
surements at the high altitude test facility P4.1.

**Flame Spectroscopy**

In LOX/GH2 and LOX/CH4 flames the OH radical is
formed during combustion and its chemilumi-
nescence is used as indicator for the reaction front
(Fig. 1.77). As in the case of flow visualization high
speed cameras are used to resolve transient ignition
phenomena.

There is not much experience available in literature
on the spectroscopy of storable propellant flames,
like nitrogentetroxide and monomethylhydrazin.
DLR in cooperation with Astrium is currently prepa-
ing experiments dedicated to gain basic knowledge
on the flame emission and the spectral transmission
of these hypergolic flames.
IR-Thermography

Infrared-thermography has become a well-requested diagnostic tool in recent times. Applications range from surface temperature measurements of apogeums motors to validate thermal models (Fig. 1.78), temperatures on the inner wall of expansion nozzles to determine flow separation (Fig. 1.79), and to survey the thermal loads on the ceramic nozzle expansion of the Vinci engine at P4.1.

Figure 1.78: IR image of an apogeum motor (courtesy EADS Astrium)

Figure 1.79: IR image of a reattched flow condition inside a thrust optimized parabola cold flow nozzle with overlaid contour grid

Coherent Anti-Stokes Spectroscopy (CARS)

As to day, CARS is the only non-intrusive quantitative method that delivers data from the inner combustion volume of high pressure combustors. CARS have been applied in model combustors at P8 and at the ONERA test bench MASCOTTE at pressures up to 60 bar.

An example of CARS transitions recorded in a LOX/CH4 flame is shown in Fig. 1.80. The focus at the Institute of Space Propulsion is on the CARS spectroscopy of the hydrogen molecule, which is a suitable probe molecule in LOX/H2 as well as in LOX/CH4 combustion. In tight cooperation with the Institute of Non-linear Optics from the Russian Academy of Sciences, laser-systems and spectral analysis tools have been adapted to high pressure and high temperature conditions (this work was funded by European INTAS- and FP6-projects). Also CARS spectroscopy of the water molecule is applied to probe not only the reactant H2 but also the reaction product H2O.

Figure 1.80: CARS-spectra recorded in a LOX/CH4 flame.

CARS is delivering temporally resolved data, thus the temperature fluctuations due to turbulent mixing and combustion are mapped. CARS provides not only insight into the progress of combustion but also into the turbulent mixing processes. From the spectral features of the CARS signals density information with respect to the probe molecule can also be extracted. CARS is therefore a key diagnostic technology for generating data for the validation of models and simulation tools for high pressure turbulent combustion.

Laser Induced Gas-Breakdown Spectroscopy (LIBS)

The LIBS technique is used to determine the composition in the probe volume in which a pulsed high energy laser has induced a gas breakdown. The gas breakdown can be either in gaseous mixture or at a solid surface. From the spectral analysis of the plasma emission the species contained in the probed gas volume or in the solid surface are determined.

The LIBS technique is expected to contribute to the diagnostics of high pressure mixing processes. Laboratory experiments to analyse LIBS spectra at well defined conditions at pressure up to 40 bar are currently performed in the laboratory.
The other application is the characterization of the spectra of solid materials in order to be compared with spectroscopic data from rocket plumes. Here the objective is to contribute data to support the analysis of operational anomalies.

**Pressure Sensitive Paint (PSP)**

The optical pressure measurement method PSP is based on the physical properties of so called luminophores. Activated by light of the right wavelength these organic molecules can achieve a higher energetic level and return to their basic level by emitting light (fluorescence). This deactivation can also be affected by collisions of suitable molecules (e.g. oxygen). In this case the luminophores react with phosphorescence.

Cold flow subscale tests conducted at test facility P6.2 use the property of the PSP layer to react with oxygen in the ambient air but not with nitrogen. The region of the attached nitrogen flow appears bright (Fig. 1.81), whereas the backflow region clouds. The intensity change marks the separation of the boundary layer, fading into the shear layer of the free jet. The PSP method was developed by DLR Göttingen in cooperation with the Aerodynamic Institute Moscow (TsAGI).

**Back Flow Frosting (BFF)**

The inhouse developed BFF visualises the flow separation in cold flow subscale nozzles using the behaviour of nearly saturated air at its dew point. The separated overexpanded exhaust jet entrains ambient air inside the remaining end part of the nozzle. The resulting backflow accelerates due to the narrowing cross section along the inner nozzle wall and therefore decreases in pressure and temperature, passes the cooled nozzle wall downstream the separation line and forms hoarfrost forms out, determining the physical separation (Fig. 1.82).

**Laser Wave Length Pyrometer**

The absorption of the laser loaded surface at elevated temperatures can be measured using a pyrometer with an identical wave length as the laser. High end transfer standard pyrometer, like IMPAC IS12-TSP shown in Fig. 1.83, allows for temperature measurements with an accuracy of ± 0.15% of the measured value ± 1°C at a measurement range between 430 and 1300 °C.

**Deformation Measurement System**

The deformation of the test specimen (e.g. TMF panel) is measured by an image correlation system as shown in Fig. 1.84. In order to obtain the highest possible measurement accuracy, a system consisting of two 16 Mega Pixel cameras was selected. This measurement system requires the application of...
small speckle marks to the surface of the test specimen and allows for the measurement of a 3D, 3 component \((u_x, u_y, u_z)\) displacement with a measurement uncertainty of less than 5\(\mu\)m.

Figure 1.84: Stereo camera system for deformation measurement
2. Engineering

2.1 Ariane Test Facilities

From the very beginning, Lampoldshausen has been involved in all European launcher programs and one of its main tasks has always been the design, construction and operation of rocket propulsion test facilities.

The test centre Lampoldshausen represents a value of 320 Mio. Euro investments. The effort to operate the facilities amounts to approx. 30 Mio. Euro per annum. A well trained staff of about 150 FTE with an average experience of 15 years maintains and keeps the complete test site operational. The Vulcain 2 engine development tests are performed on the P5, a 180 Mio. Euro test bench, Lampoldshausen’s biggest facility. The Ariane 5 ME development project relies on Lampoldshausen’s unique high altitude facility, the P4.1 test bench.

Currently the engineering department is developing the stage test bench for the ARIANE 5 ME upper stage – a 15 Mio. Euro project – and is involved in the feasibility study for Europe’s Next Generation Launcher (NGL). For the latter ESA provides funding with the FLPP program (Future Large Preparatory Program). In this context the Institute of Space Propulsion in Lampoldshausen will provide a feasibility study for the tests of the first demonstrator engine at the P5 facility.

The core competences of engineering are the design and construction of test benches for rocket engines custom tailored for European projects, especially the evolution of ARIANE. Within this context the engineering department’s portfolio includes management of the future test requirements and the ability to generate costed development projects for the different test benches. Moreover, technology and research programs are supported by the department.

The engineering department provides the full system competence for the design and construction of all Lampoldshausen test benches. Competencies in the following areas are of strategic importance: operating behavior, high altitude simulation, hot gas exhaust systems, cryogenic and gaseous feed systems especially with stage like supply conditions and standardized or unique user requested measurement, control and command systems and technical project management.

Competencies which are not directly linked to the design and construction of test benches include the application of new materials or manufacturing options for model combustors or test equipment, the numerical simulation of flow conditions and test loads validated by experimental data, special measurements with analysis/interpretation of the results.

The engineering department is organized in three groups; facility development, research and technology support and measurement control and command systems.

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Figure 2.1: Organization Engineering

In addition to the design of subsystems the engineering department has the leadership for the erection of whole test facilities. The latest large project was the realization of the high altitude test facility P4.1 to test the VINC1 engine in vacuum conditions. P4.1 is currently the major test facility to ensure the success of the whole Vinci program.

The basic competence to perform this kind of development project was transferred from the altitude simulation test facilities P1.0 for satellite engines and P4.2 for the AESTUS engine years before. The qualification of the rocket engines for in space flight engines on the DLR Lampoldshausen test site is a key element for the European product approval decisions. The collaboration within the working groups of DLR, CNES, ASTRIUM and SNECMA personnel is mandatory and permanent attention has to be given that the work packages are clearly defined in a proper way. Therefore, the latest standards in project management capability are applied within the engineering department.

Decisions for stage testing the Ariane5 ME upper stage are in progress. DLR Lampoldshausen is the main European Excellence Center which is able to support this large ESA development project.
2.2 High Altitude Simulation Test Facility P4.1

In this chapter the high altitude simulation test facility P4.1 is used to demonstrate the special competences of the engineering department described before.

Final acceptance of the P4.1 with the new upper stage engine VINCI including the large extendable nozzle was successfully achieved in 2010.

The task of altitude simulation consists of creating the test condition within a vacuum cell. This is primarily low ambient pressure of just a few mbar. Special operational conditions are linked to the transients during Start-Up and Shut-Down of the engine with respect to the nozzle loads. Maintenance of the vacuum with the running engine is achieved by using the energy of the exhaust jet. The supersonic gas flow is decelerated and compressed by a diffuser. Additional extraction of the exhaust gas by steam jet ejectors and condensation maintains the necessary pressure conditions.

To provide the large quantities of steam, rocket steam generators are used. The principle of rocket steam generators is to inject water into the hot gases of a rocket combustion chamber.

The challenges for the P4.1 altitude simulation require new technologies. Notable are the use of adapters to test different test configurations on the same test position, the use of a centre body diffuser and the stage like supply conditions. Special attention is given to the dynamic behavior of the altitude simulation. The big nozzle structures are very sensitive to loads during transient phases. Powerful steam ejectors adapt the pressure condition in time to the transients of the VINCI engine during start up and shut down for reduced nozzle loads.

2.2.1 Center Body Diffuser P4.1

The super sonic diffuser converts kinetic energy of the jet to pressure energy. The efficiency and stability depends essentially of the ratio of length l to diameter D. An optimal ratio of l/D is between 4 and 8. A centre body diffuser has a similar behavior like a second throat diffuser. The second throat is realized by a ring channel around a centre body. The overall length of the diffuser is short because of the reduced hydraulic diameter of the ring channel. After starting of the supersonic flow, the flow conditions are stable down to lower pressure ratios (Hysteresis). The disadvantage of the cooling effort of the centre body has been managed.

CFD calculations and diffuser sub scale tests with cold and hot conditions were performed to verify the heat loads and functional behavior.

The cold gas (N2) testing was done with similar Mach numbers at the test facility P6.2. The objective was the verification of the basic design and investigations like Gimballing of the engine and transient studies.

The hot gas model was tested at the test bench P8 with a H2 / O2 combustion chamber and similar test conditions to VINCI (60 bar chamber pressure, mixture ratio of ROF = 6). The objective was the verification of the modeling especially the verification of the heat loads and flow conditions like the supersonic Start during engine ignition and UN-start conditions during engine shut down. Especially the non-start condition triggers the loads of the nozzle by a pressure drop and back flow.

![Figure 2.2: Heat Loads Hot Gas Model](image)

![Figure 2.3: Subscale models P4.1 diffuser](image)
With the experience and data of the hot gas subscale tests the design of the P4.1 centre body diffuser was improved especially for the heat loads.

Figure 2.4: Centre Body Diffuser P4.1, $\phi = 2380$ mm

The load cycles were simulated by a cutting torch to verify the behavior of the cooling channels, the surface protection for corrosion and the failure case of cooling.

Figure 2.5: Load Cycle Test

2.2.2 Rocket Steam Generators P4.1

The main design drivers during the development of rocket steam generators are steam consumption, cost reduction and all boundary conditions which are defined by the standards to keep the impact on the environment at a minimum.

The concept is based on a rocket combustion chamber operated by ethanol and liquid oxygen ignited by a hydrogen / oxygen pilot flame. Special research and technology programs have been performed for the development of the injection and combustion system. Acoustic absorber baffles had to be integrated to control the stability of the combustion.

One very special feature of the design is the position of the sonic cross section. In opposite to standard rocket engines it is not designed into the combustion chamber itself, it has to be placed inside the steam nozzle, i.e. several meters downstream. This influences the ignition and start up of the combustion. Therefore, the steam generator is developed in two steps, the combustion chamber mode like a rocket engine and the steam generator mode with mixture chamber, steam lines and steam nozzle.

Several units with 4.5 kg/s steam up to 60 kg/s steam were developed and are currently operational. The steam generator plant of the P4.1 is equipped with 5 steam generators of total 240 kg/s steam generation equivalent to about 600 MW thermal power. The maximum operational time is 1000 s.

Figure 2.6: Steam generator with 60 kg/s steam

Figure 2.7: Infrared display of the steam generator 60 kg/s
2.2.3 Modular Configuration of P4.1

The altitude simulation P4.1 is designed to test the different test configurations of the VINCI engine at the same test position. The configurations are the chamber with expansion ratio of $\varepsilon=22.3$, VINCI with the fixed nozzle of $\varepsilon=93$ and VINCI with the expendable nozzle of $\varepsilon=243$. The flexibility is achieved by using a family design method for different adapters.

![Figure 2.8: Test Configurations VINCI](image)

2.2.4 Feed System P4.1 for LH2 and LOX

The definition and control of the feeding conditions of a launcher is the principle task to define, design, simulate and finally operate the engine supply system. It is the critical interface between engine and stage and of course the critical interface within the test facility.

The request of stage like and flight like interface conditions especially the pump inlet pressure requires special technologies. For the VINCI test facility P4.1 the feeding system is equipped with buffers to simulate the stage feeding conditions during Start Up and Shut Down.

During chill down, ignition and start up the engine is supplied by the buffer. After reaching steady state conditions the supply is switched to the run tank. During shut down of the engine the buffer is usually connected again to prevent damage because of the water hammer phenomenon. Important parameters are the hydraulic behavior of the lines, the resistance, the characteristics of the valves and the volume and pressurization of the buffer. The simulation of the flow dynamics within the feeding lines is successfully performed with a validated “Lumped Parameter Model” calculation.

![Figure 2.9: VINCI with fixed nozzle $\varepsilon = 93$ and simulation flow field](image)

2.2.5 P4.1 Operational Conditions

The VINCI is mounted vertically within a thrust measurement system inside a vacuum chamber. To verify the operational behavior of the P4.1 different modeling activities are performed. The driver is the understanding and prediction of test conditions.

The diffuser is capable to maintain less than 4 mbar inside the vacuum chamber. This specification is maintained also when the engine is fired and for all other operational points. For the test preparation the system can be evacuated by mechanical pumps up to the vacuum flap. The very fast closing of the vacuum valve in less than 1 s avoids damages of the engine in case of failure. The suction system with the first ejector system, the condenser and the second ejector system sustains the vacuum against ambient conditions. By barometric draining the warm water of the condenser is guided to the underground storage keeping the vacuum inside.

![Figure 2.10: General Lay Out P4.1](image)

A special task is the verification of the test data. CFD simulations of the test data support the understanding and the management of the dynamical conditions during shut down.
2.3 Measurement, Command and Control System (MCC)

The new measurement and control system of the test facility P5 is used to demonstrate the latest standard of today’s MCC systems. The system is in operation since 2009.

A common working group of SNECMA and DLR - Engineering developed a “General Specification For Measurement and Control Command Systems for the ESA Ground Facilities”, presented for ESA and CNES in 2005. The purpose of this document is to present the need in terms of requirements for a Technical Specification for a "MCC" system (Measurement and Control-Command) for the ground facilities of Snecma Moteurs (Vernon, France) and DLR (Lampoldshausen, Germany). The major characteristic of what is called the "MCC" system is its ability to control all functions in real time. This includes signal conditioning, acquisition systems, process computers, process imaging but also the Back-up (security) system which is included in this notion.

For decision a common document “MCC System Benchmarking Specification for ESA Ground Facilities” was created by SNECMA and DLR. The aim of the benchmarking is to evaluate several solutions from different companies in order to compare them to the common specifications.

These solutions are always be judged on the following parameters:

- Safety and technical aspects
- Investment, operational, maintenance and benchmarking costs
- Scaling possibilities
- Company management,
- Reference list
- Quality assurance.

Based on these general specifications the new MCC system of P5 was designed by DLR. A consortium of the companies WERUM, SEA and CEGELEC was chosen to realize the project. The first VULCAIN 2 test in real conditions was successful performed in June 2009.

Safety was the first driver for the design. Testing at rocket engine test facilities has to be very flexible in order to use the full advantage of testing on site rather than during inflight conditions. The test requests and test configurations usually vary a lot between the different single hot runs. Possible failure scenarios have to be analysed, detected and excluded before the tests. The real time system has to be setup in a way to react automatically within milliseconds to shut down in case of emergency or red lines.

The system stores analogic and digital data up to 15 MByte/s acquired by more than 2000 sensors. Parallel the system has to visualise 8000 parameters at 14 operator terminals.

An essential function is the command and control of the facility. User interfaces are implemented in a way to provide the operator immediately with information about the relevant data of the hot runs.

With the P5 system it was the first time a real distributed system for integrated data acquisition and real time commanding was designed and realised. The test data back up is performed online during test on several integrated data servers. Therefore, the test data is directly available for further processing.
2.3.1 Central Data Treatment System CTS

The test data of the different test benches (no engine data) are transferred and stored on a central data treatment system (CTS). This system allows analysis of the facility behavior without interaction to the test bench itself. Besides the data management system “Dynaworks” additional special analysis tools are available like fast Fourier transformation for dynamical analysis or the correlation of different data for transfer functions. Permanent improvement of the CTS is necessary and assured.

Drivers are:
- Higher capacity for future programs (increasing test benches, higher acquisition frequencies)
- Generation of Reports
- Improved security rules
- Efficient and secure offline archiving functionality.

2.3.2 Calibration Lab

The calibration lab is responsible for the calibration of pressure transducers, differential pressure transducers, transmitters and gauges, inventory management for transducer, selection and procurement of transducers, adaptation of transducers, laboratory services, maintenance and DKD (German Calibration Service) certification, transducer database.

The range of calibration is between 0,0001 bar up to 800 bar. The set of grid coordinates emerging from calibration is used to calculate the coefficients of an (n)th degree polynomial by regression calculation.

\[ P(x) = A_0 + A_1 \cdot x + A_2 \cdot x^2 \ldots + A_n \cdot x^n \]

The calibration record of a transducer contains the transducer parameters, the polynomial coefficients, set of grid coordinates and the fault of actual value to target value.

2.3.3 Developments

The electronic lab for developments of special measuring and control equipment and accessories assures quality control and development of features and precision which are not available on the market.

The analogue signal conditioning unit (AS) is an example for these developments. The requests are basically defined by the research facilities like
- high flexibility for signal conditioning
- easy handling
- high variability for the used types of sensors
- high reliability
- less complexity.

Actual the AS4 is developed and more than 400 units of the different development steps AS1 to AS4 are in use.

2.4 R&T Support

Engineering projects and the support of technology and research projects are handled by a design office and a small workshop which is directly linked.

The design office uses the tool CATIA V5 to design constructions and arrangements in 3-D for engineering, specifications, presentations, procurement and manufacturing. A special task is the provision of CATIA models which can be directly used for the grid generation for further treatment in CFD or structural analysis.

The work shop is needed for the operational availability of the test sides. In case of mechanical problems at the test benches the work shop is able to provide immediate help regarding necessary bench equipment. Additionally the work shop supports
the scientists in the departments of technology, propellants and rocket engines during the design of the test specimen. The hardware is developed in close cooperation between craftsman and scientist.

The education of the craftsmen is in close cooperation with the test facility operation and custom tailored to support the special needs of test centers, e.g. measurement equipment and instrumentation issues.

2.5 Outlook

2.5.1 Ariane Evolution

Main driving force for future requests is the evolution of Ariane. The engineering of the stage test facility for Ariane 5 mid life evolution has already started. A new test position P5.2 is to perform the qualification of the new upper stage with the VINCI engine beginning in 2013. The main design drivers are the cost issues, the test requests, and the safety conditions. Especially the common bulkheads at the cryogenic flight tanks for liquid oxygen and liquid hydrogen require the verification of the safety conditions. The analysis of LH2/LOX explosion with regard to the evacuated safety areas and constructions is ongoing. The data of failures of upper stages during the Saturn program in USA provides valuable information. For modeling, FLACS (Flame Acceleration Simulator) from the Norwegian company GEXCON is used.

Within the FLPP program of ESA a demonstrator test for the high thrust engine of the next generation launcher is planned. The engineering department is investigating the use of the test facilities P3 with the thrust chamber assembly and the engineering department has started at the P5 with a complete engine investigation. In 2018 the test of a demonstrator engine in the thrust level of VULCAIN II is foreseen.

2.5.2 High Altitude Simulation

The high altitude simulation has to be improved for the future challenges. Drivers are new nozzle designs with high expansion ratios, new materials like ceramics, advanced nozzles like expandable nozzles or dual bell nozzles and throttled engines with variable thrust levels require new technologies for testing close to flight conditions.

An engineering project “Advanced Altitude Simulation AAS-P8” was initiated to develop and design an experimental setup to improve the altitude simulation and to test nozzles with flight loads on a subscale level. The basics are:

- Subscale combustor with hot gas conditions
- Variable and adjustable pressure conditions 1bar – 100 mbar
- Surrounding flow conditions up to M=2

Start of operation AAS-P8 is foreseen for 2013.

Figure 2.15: AAS-P8 test chamber

At the cold gas test facility P6.2 investigations were performed with variable vacuum pressures and surrounding flow conditions. These investigations are basis for the engineering AAS-P8.

2.5.3 Test Facilities

To maintain the operational conditions of the test facilities there is an ongoing development of the necessary technologies to respect the legal requirements and orders like noise emission and to improve the growth potentials of the installations.

On the P8 a new exhaust gas guiding system is developed for the research in noise reduction by special water injection. The first testing will be performed in 2011.

The source of noise emission is the free supersonic jet. There is the knowledge of noise reduction by water injection. Driving parameters are the water supply, the water injection and spray conditions.
2.5.4 Technical Plant for Cryogenic Applications

There is an increasing demand for cryogenic competence. The tasks of the technical plant for cryogenic are:

- **Hydrogen** for mobility, handling and operation of components and infrastructures, modeling of conditions
- **Safety**, procedures, hardware and modeling of failure conditions.
- **Technology**, testing of cryogenic components

The available engineering support on the market for special unique cryogenic applications is critical. To maintain the competencies and experience and to support the engineering a project for a technical plant of cryogenic investigations and applications is started. The cryogenic plant is a platform for testing and investigation in cryogenic fluids and equipment especially measurement device. The available infrastructure will be used like:

- storages of 1000 m³ LH2 and 500 m³ LOX
- H2 & N2 supply up to 800 bar, He up to 230 bar
- Safety infrastructure
- Handling and operation procedures and experience of cryogenic facilities,
- Design, commission, reception and maintenance of cryogenic facilities
- Measurement and Control of cryogenic.
3. Department of Safety, Quality and Technical Services

General:
The site of Lampoldshausen with its test and supply facilities is subject to the restrictions of the German law BundesümschutzGesetz (derived from the European SEVESO-II directive) and its relevant ordinances, especially the Hazardous Incident Ordinance. Because of the complex framework effort which guarantees safety and security, Lampoldshausen has invested in people and processes in order to respect the restrictions of all relevant laws and ordinances as well as to guarantee the protection of people and the environment. The department of safety, quality and technical services maintains a very high standard with a team of about 40 qualified employees.

In addition to the essential duty to assure health and safety, the department has a number of important tasks on the site Lampoldshausen, such as:

- Operating of the Safety Management System according to statutory order on hazardous incidents (SEVESO-II-Directive)
- Maintaining and upgrading of the operation authorization
- Keeping up and improving of the Integrated Management System – IMS
- Quality assurance for operation and maintenance of all test facilities
- Ensuring the supply of the site Lampoldshausen with water, energy and pressurized air
- Operation of the wastewater treatment plant
- Site maintenance and car service.

All these tasks and services are needed to operate ESA’s test facilities for the ARIANE 5 and the other programs. Special processes have been implemented to manage third parties, e.g. EADS. The challenge is to fulfil all existing and upcoming requirements regarding the existing and planned test programmes and to harmonize them with the German and/or European laws. It is the department’s main duty to keep up DLR’s exclusive operating licence in Europe to perform tests with cryogenic and storable propellant stages.

Organisation:
The department is divided in three sections, the safety section, the quality section and the section for technical services. The head of the department is also the hazardous incidents officer of the site and the management representative for the Integrated Management System and reports directly to the director of the institute. Furthermore he acts as the interface to the regional council and all other responsible authorities in terms of safety, health and environment questions concerning the operation permission.

3.1 Safety Section

The safety section consists of 13 employees lead by the manager of the safety center who is located in the main building I1A. The team consists of the 4 employees from the plant fire brigade, the 8 members of the safety operating team and the ambulance. Plant security is managed by the head of the safety control center.

![Figure 3.1: View inside the safety control center](image)

The tasks of the safety section are:

- Operational safety management for test activities
- Fire prevention and protection
- Security services
- Operational safety provisions for workers
- First Aid
- Environment protection
- Operation authorization
- Provision of trainings concerning safety, environment protection and health
3.2 Quality Section

The quality section consists of 5 employees which are mainly dedicated to the different ESA projects on the site Lampoldshausen. Main tasks are:

- Quality assurance for maintenance and operation of all test facilities
- Quality assurance of all test activities
- Treatment of Non-Conformances (NCR)
- Quality assurance of the customer’s test specimen
- Configuration management of the test specimen during test campaigns.

The quality engineers supervise all processes of the ESA projects and check their compatibility according to the relevant procedures. The procedures are part of the Integrated Management System (IMS) which guarantees a high quality, safety and environmental standard of all concerned test activities. Therefore yearly audits are performed to keep the certificate for DIN EN ISO 9001, DIN EN ISO 14001 and BS OHSAS 18001.

3.3 Technical Services

The technical services on site consist of a team of 4 technicians to operate, maintain and to renew all kind of electrical supply and control systems for the general needs of the area, such as:

- 20 kV- supply net
- 400 V supply
- 230 V supply
- Emergency power supply
- Interrupt free power supply
- Command and signal net for the hazard alert system, IT, telephone, light signals and other services.

Additionally, a team of 5 technicians is operating and maintaining the complex water supply system for the general supply of the site with drinking, cooling, distinguishing and ultrapure water. They are also responsible for operation and maintenance of the waste water plant. This plant was built up during the year 2010 and fulfills all actual requirements concerning water quality to be led into the river.

The systems are in detail:

- Own well for process and drinking water (7 l/s – 1 l/s)
- 2 water towers with 600 m³ capacity for process water
- Water tank for drinking water
- Distribution network for ultrapure water
- Biological clarification plant
- Mobile air compressor.
The third team consists of 3 employees who support the institute with all other necessary services, i.e.:

- Maintenance of all plant cars on site for test and support
- Purchase of new cars and disposal of the old
- Winter services
- Site services
- On site transports
- Waste management.

Figure 3.4: View of the new biological clarification plant

Figure 3.5: New electrical car for maintenance work on site
4. Operation of Test Facilities

4.1 Background

The test site in Lampoldshausen was established in 1959 for the purpose of constructing test facilities and for testing rocket propulsion systems. The test facilities P1 and P2 were the first to be erected at that time. Later on in the frame of the European Launcher Development Organisation (ELDO) the test facilities P3 and P4 were erected in 1963.

All these test facilities are still in use today. Continuous modification and modernisation have ensured a state-of-the-art standard on all test beds.

After the end of the ELDO program a new era began in Lampoldshausen: the development of the ARIANE launcher family.

The successful Ariane programs have all been managed by the European Space Agency (ESA). Several facilities in Lampoldshausen are actually owned by ESA.

For clarification: According to German law, DLR is the legal owner of the facilities and ESA is the economic owner of the facilities.

The regulations which apply to these facilities and which define the obligations and rights of the two entities ESA and DLR are contained in the so-called ESA-DLR asset agreement. This agreement has been in place uninterrupted, since 1975 and is based on the regulations from the time of the ELDO contracts.

During ARIANE development mainly the facility P4 was used in order to develop and qualify the Viking engines, the complete second stage, and the liquid propellant boosters (PAL).

The decision to develop the launcher Ariane 5 in 1995 had a huge impact on Lampoldshausen: the test facility P5 and the associated cryogenic infrastructure were built. The P5 went into operation in 1990 and was used for the development and qualification of the main stage engine Vulcain. Additionally the P4.2 was adapted in order to be able to test the new upper stage engine AESTUS.

Since the beginning in 1959 the test facilities have been modified and adapted in order to perform different testing activities for various different programs. The know-how of DLR Lampoldshausen increased quickly and the test site in Lampoldshausen became indispensable for the ARIANE 1 to 4 and ARIANE 5 development programs (see figure 4.1). In all future programs such as the development of the new cryogenic upper stage for Ariane 5 using the Vinci engine and further programs under ESA guidance, the DLR Lampoldshausen test site will play a major and very important role due to its unique experience and know-how.

DLR Lampoldshausen needs to continue its successes in order to ensure success especially for the European launchers and programs.

4.2 Definitions

Several specific terms and abbreviations are used repeatedly throughout this report to characterise the status and functions of the test facilities. They are summarized here for clarification.

ESA Programs will be named as follows:

- **ARTA** (= Ariane Research and Technology Accompanying Program): this program ensures parallel to the flight activities the availability of all means necessary to maintain flight readiness, to solve problems encountered during flight or to implement improvements to the launcher.
- **FLPP** (= Future Launcher Preparatory Program): this program is preparing the technologies necessary for the development of future European launchers
- **A5ME** (= Ariane 5 Midlife Evolution): this program deals with the development of the new Ariane 5 Cryogenic Upper Stage using the Vinci engine

Since 2007 the ESA test facilities under the responsibility of DLR at Lampoldshausen are maintained based on a direct contract from ESA to DLR.

The general goal is to ensure the maintenance in operational conditions (MCO) of ESA owned strategic engines tests facilities. The principle for ensuring this MCO, concerning Ariane launch system is based on:

- the provision by ESA ARTA Program of a continuous and basic maintenance of those test facilities, and
- the coverage by the users of any other costs related with the use of those facilities above the mentioned basic maintenance.

For the ESA test facilities a frame contract ensures the financing of the basic maintenance of those facilities. Other costs need to be covered by the users of the facilities (e.g. propellants, operational maintenance).

The status of an ESA or DLR test facility is either:

- **Operational** ("en service"): the facility is currently performing test campaigns, maintenance is nominal;
- or **Active waking** ("veille active"): the facility needs a pre-configuration phase in order to acquire its operational status in about 1 month at low cost, maintenance is reduced due to the absence of test activities;
- or **Cocooning** ("dormant"): the maintenance is reduced to the minimum but still allows to bring the facility to its operational status after a few months of refurbishment and for a higher cost than from active waking;
- or **Stopped** ("à l’arrêt"): the facility is not available; in this status a test bench cannot be used for test unless a complete refurbishment phase is carried out to bring the bench to operational status.
- or **Run down / Run up**: the transition or reconfiguration phase from operational status to basic maintenance status is called run down, the transition or reconfiguration phase from basic maintenance status to operational status is called run up.

Different types of activities are necessary to keep the test facilities in operational condition depending on their configuration status and renewal needs:

**Nominal or Full Maintenance**

This covers all activities aimed to maintain the test facilities in their operational status during the execution of test campaigns, by means of preventive and curative maintenance actions, including the replacement of standard parts and equipments.

**Renewal due to obsolescence (Renewals)**

This covers the renewal of equipment, which can no longer be maintained due to its obsolescence or the obsolescence of its main component parts (i.e.: no longer procurable).

**Upgrade to comply with law (Upgrades)**

This covers the modifications or replacement of equipment which is non-compliant with new laws and regulations.

### 4.3 Organisation Department of Test Facilities

#### 4.3.1 Responsibilities of the Department

The responsibilities of the department of test facilities are:

- Overall management of the respective facilities
- Operation of the respective facilities
- Maintenance of the respective facilities
- Modification of the respective facilities
- Assurance of the safety of the respective facilities
- Identification and Correction of problems, identification of preventive measures
- Analysis of the behaviour of the facilities and derivation of corrective actions if necessary
- Contact to the users of the facilities and to ESA (in case of ESA facilities)
- Identification of needs for upgrades or renewals of the respective facilities
- Performance of hot fire tests for DLR’s own purposes or for external users.
4.3.2 Organisation

In order to perform these activities, the test facilities department is organized in three main groups (see also figure 4.2):

- One group operates the cryogenic facilities P4.1, P5, P8 and P6.1
- One group operates the storable propellant and/or high altitude facilities P4.2, P4 Steam Generator and P1.0 as well as the thrust chamber test facility P3.2
- One group operates the supply facilities; the team members are specialized craftsmen who are qualified to work at the different facilities.

Some specific topics are organized outside these three groups. These are for example

- Management of the Renewals and Upgrades of the facilities
- Controlling for Test Facility specific projects
- Project Assistance
- Specific functionalities such as e.g. Explosion Protection authorized representative.

Although it is not possible to operate all facilities in parallel with the current teamsize, several test benches are operated independently. This is important where certain tasks are required to be performed at the same time, e.g. at P4.1 and P4.2 where different engines for different users are tested.

Nevertheless, it is required to keep the test teams as small as possible for financial reasons. Because of this decision, the two biggest facilities P4.1 and P5 cannot be kept in operational status at the same time. All other facilities can be operated in parallel, albeit with an impact on flexibility and test cadence.

Therefore, the status of the operational phases on the big facilities is alternating and is a challenge with respect to organisational aspects. The teams operating the facilities always need to be able, normally within one month, to switch from one to another, e.g. from operation of the facility P5 to the operation of the facility P4.1.

This is especially challenging, if the facility was not in operation for a long period of time (e.g. 1 year or more). In order to be able to do this, it is necessary to not only keep the technical status of the facilities under close supervision and maintenance, but also the training status and the flexibility of the team.
4.3.3 Training of Personnel

The above mentioned special requirements as well as general staff fluctuations make it necessary for the staff to receive special training or preparation for their tasks in the test team. In addition to the in-house DLR training program experts are contracted to teach the necessary knowledge or methods. This is mainly done for specific equipment such as training with respect to e.g. hygrometry measurements, mass spectrometer operation or the use of forklifts or cranes.

Certain training is also necessary for all personnel for safety aspects. Hence, regular instruction sessions are performed especially with respect to the use and handling of dangerous products such as the propellants stored in large quantities on the test facilities.

Furthermore the department of test facilities has developed a dedicated course program for the training of its craftsmen (mechanical and electrical). This internal program was acknowledged in August 2001 by the authorities and, if successfully completed, results in a salary increase.

The basis for this acknowledgment is the fact that the demands requested from the craftsmen are very high in terms of accuracy and responsibility because of the handling of the complex, expensive and unique hardware. Mistakes in the handling can lead to high costs in maintenance and campaign performance.

This course program is consisting of a stepwise structured training program which is to be held by internal specialists due to the uniqueness of the facilities, test specimen and processes.

The training program includes 4 modules. Each module has to be concluded by a certificate which is created when the trainee has successfully performed a written test.

The duration of the training course is 4 years. One module per year is possible. The correct performance of the training course is checked regularly through the certifications in the frame of the Integrated Management System of DLR Lampoldshausen.

In addition to such standard training there are also team training sessions performed for the respective test bench teams in order to improve operational procedures, communication and co-operation which are essential aspects in order to perform safe and successful test campaigns.

4.4 Overview

On the following pages an overview of the site of the DLR test center in Lampoldshausen is given. The facilities which are under responsibility of the department for test facilities are marked in bold letters. The ESA facilities are also marked by an asterisk *. All ESA facilities are under the responsibility of the department of test facilities in order to establish one dedicated communication interface to ESA.

The facilities are described in more detail in the following chapter 5.
<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
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<td>D68</td>
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<td>Material Stock</td>
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<td>Garages</td>
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<td>Test Facilities 4.1, 4.2, Steam Generator</td>
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<td>T53</td>
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<td>T58*</td>
<td>Hydrogen depot</td>
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Figure 4.3: Overview Over the Test Site at DLR Lampoldshausen
4.5 Management, Offers, Contracts

4.5.1 Background

When the test facilities are used for testing activities with hardware from other companies, it is essential that clear and legally binding regulations are in place. This means the negotiation of different contracts with different entities for each test facility.

Furthermore not only contracts for testing are to be established but also for erection or modification of facilities.

The contractual structure for the ESA facilities is quite complicated since several entities (ESA as economic owner, industrial companies as users and DLR, as operator and bench responsible) are involved.

Figure 4.4 shows an overview of the ESA contracts which are currently in place for the department of test facilities. The basis of this contractual relation is the ESA – DLR Asset Agreement. Within this framework several Work Orders (WON) are placed which are also contracts regulating dedicated aspects of design, maintenance or operation of the ESA test facilities.

Under each Work Order further so-called CCN (Change Contract Notes) may be placed, if it is seen in the course of the performance of the contract that the conditions and / or the scope of activities need to be adapted.

It has to be pointed out that for each user contract Work Orders and CCN also exist. The contract with the user may be a frame contract or a nominal contract.

Figure 4.5: Schematic of contracts on ESA facilities

For the basic DLR facilities the contractual situation is different.

For P1.0 a frame contract with the main user Astrium is in place. Each test campaign is then ordered by Astrium under a standard set of contractual conditions. If another test facility user approaches DLR, specific contractual conditions will have to be negotiated.

For P6.1 one nominal contract is in place with Astrium for the performance of a dedicated test campaign. This contract is normally the baseline for further contracts with Astrium or with other possible users.

For P8 a specific situation exists. The P8 is a European Technology and Research Facility. Its erection was financed by the four entities DLR, Astrium, Snecma and CNES. The operation of the facility is done by the department of test facilities which has in place contracts with all the above mentioned entities. These entities are up to the present day the sole users of the facility. The relationship between these entities is regulated by a specific MOU (Memorandum of Understanding). In this MOU the maintenance and operation of the P8 is defined. Further details to this test facility are given in chapter 5.9 of the present report.

A contractual relation with users of test facilities is usually established in the following way:

- Offer compilation
- Contract negotiations
- Contract performance
- Monitoring and Control.
4.5.2 Offer Compilation

First the potential user defines the basic necessities and objectives of the foreseen test campaign and then establishes contact with the department of test facilities. This is normally done by way of a so-called RFQ (Request for Quotation) which may include technical as well as contractual requirements and documents.

The department of test facilities checks the compatibility of the user requirements and the test specimen with the existing test facility. Additionally the compatibility with DLR internal regulations is verified. Deviations are listed and suggestions for corrections are developed.

Already at this stage the organisation of the later execution of the activities has to be clear and is passed on to the potential user e.g. by naming work package managers.

Once the inquiry has been thoroughly understood, the test facilities department team draws up a list of resources which is used as the basis for costing calculations. The list of resources and preliminary costing calculations, as well as any anticipated deviations, are then co-ordinated with the central DLR division for contract handling in Cologne and the offer is established. This offer is then sent by the administration in a legally binding form to the potential user, according to the DLR directives.

4.5.3 Contract Negotiations

Price, schedules and contract conditions are negotiated on the basis of the offer.

The central DLR division for contract handling in Cologne supports the DLR department of test facilities in Lampoldshausen during the contract negotiations. One dedicated contracts officer in Cologne has been chosen especially for these activities to ensure that the specific ESA contracts and tools (e.g. ECOS – the ESA software tool for building offers or ESA-P – the ESA software tool for payment and invoicing) are applied. Support from other branches of the DLR administration is organised via this contracts officer (e.g. legal support or support from export control specialists).

It should also be noted that DLR’s status as a public organization has to be respected in all contracts.

4.5.4 Contract Performance

Based on the standard project management methods the performance of the project is controlled and monitored against the targets specified in the contract. A work package manager is responsible for ensuring that the contract is fulfilled in accordance with the customer requirements concerning quality assurance, configuration management, documentation, schedule monitoring and acceptance.

4.5.5 Monitoring and Control

The performance of the activities is continually monitored on the basis of the management specifications named above.

This refers particularly to:
- costs
- schedules
- deliveries to the customer.

Cost monitoring is a purely internal affair, as projects are mainly carried out on fixed lump sum price conditions.

Schedule monitoring is an important element in the success of a test campaign and is provided by the department of test facilities. The clear structure of the deliveries (test results, activities reports, studies, fault reports with proposals for suggestions etc.) in the costed test/development program provides the maximum transparency not only for DLR but for the customer also. In this context the monitoring of the due date for these deliveries is a particularly important element to manage the payment schedule.

It is up to the work package management to prepare and proceed with planned reviews, including possible supplementary work arising from the reviews.

Monitoring and control is handled with computer assistance (workplace computer), generally using commercially available software packages. In special cases, customer – defined software is used.
4.6 Campaign Organisation and Course of Action

4.6.1 Test Preparation

Usually the campaign starts with the delivery of the test specimen by the manufacturer and user of the bench. It is possible that the manufacturer itself performs all activities on the test specimen or that these activities are delegated to DLR personnel. This is the case e.g. for Vinci or Vulcain 2 engines where DLR takes over the responsibility for all handling and installation activities on the engine. The transfer of all necessary information about the test specimen is done via a specific meeting where all anomalies, events or characteristics during the production of this specific test specimen, as well as its documented history (specimen logbooks, etc.) are discussed and handed over to DLR for further updating.

The test specimen has to be integrated into the respective facility by DLR. Then the preparation of the first hot run starts. This preparation has to be done on different levels and areas which are usually

- Connection of all mechanical interfaces from test facility to test specimen and verification of good connection (e.g. performance of seal checks)

- Connection of all electrical interfaces from test facility to test specimen and verification of good connection (e.g. hammer test on sensors, power measurement on command lines).

- Preparation and control of the test specimen itself by performing functional checks (e.g. dry testing of valves or performance of seal checks).

- Preparation and control of the measurement database on the MCC (Measurement, Command and Control System) system including conditioner and filter setting and calibration of sensors.

- Analysis of the test documentation delivered by the user (test request, measurement request, request for activities on the test specimen) and if necessary clarification with the user.

- Programming and verification of automatic sequences on the MCC system according to the requests from the user and the requirements for bench functionality.

- Programming and verification of automatic surveillances (redlines) on the MCC system according to the requests from the user and the requirements for bench functionality.

- Adaptation of regulation algorithms, if necessary.

- Filling of all media storage such as propellant tanks and cooling or purge media storage tanks.

- Filling and if necessary performance of recooling activities on the cooling water supply system.

- Verification of good test facility status (e.g. performance of switching tests or other functional checks).

- Performance of preventive maintenance activities as required by the respective maintenance plan.

- Performance of curative maintenance activities following unexpected behaviour (NCR treatment).

- Performance of a risk analysis for the planned testing together with the user.

- Documentation of all activities.

Figure 4.6: Transport of Vulcain 2 engine from M29 to P5
Work at the test facility takes place according to fixed work specifications (checklists, procedures). This guarantees the reproducibility, traceability and thus high quality of the product and the work itself. Any intervention with the engine requires written clearance from the user. DLR converts these requirements into a procedure for working on the engine. The procedures indicate the work sequences, stipulate which parts should be used and specify individual steps.

Not only for the engine, but for all activities at the test facility there are written procedures in order to ensure correct performance and to prevent mistakes. Each activity performed for the test preparation is written in a plan and in the specimen logbooks as well as in dedicated documents. These are for example a document describing the configuration and setting of all bench systems or a document describing all test specimen activities and results during test preparation.

Special meetings take place periodically for systematic preparation of the tests. All risks involved in a test have to be dealt with (risk analysis) before the test clearance is given. Planning meetings are held every week to co-ordinate the work of the various groups and to avoid clashes and hindrances.

Irregularities or faults in hardware and software are documented immediately. A standard procedure (NCR - Non-conformance report) is available to every member of staff to immediately record any non-conformance in writing. The quality department registers and manages these NCR. Every documented fault must be eliminated or accepted before the test. Elimination measures are defined by the user’s representative and the DLR test leader. A NCR is closed or accepted by these two parties and a member of the DLR quality department.

The sub-systems of the test facility and the programmed sequences are checked twice before every test. Test clearance is given when the results of these dry runs and all engine inspections are satisfactory. The engine inspections are repeated before every test and the control sequences are re-defined and tested for every test depending on variations in the test objectives.

4.6.2 Test Performance

The performance of the hot run itself is guided by the so-called chronology for the test. This document describes all necessary steps in order to prepare test facility and test specimen on the test day for a safe and successful test.

Operation of the test facility systems starts up successively on the basis of check-lists and procedures.

The test team organisation for each test facility is done by the test leader for each separate test. A weekly planning meeting of the complete test team, lead by the test leader, ensures effective communication and information flow. Several smaller meetings between members of the test team are organized if necessary. The test leader is also the communication interface to the support functions for the test from other departments such as quality assurance or site safety and the fire brigade. The test leader is also the person who communicates and discusses all technical issues with the representatives of the user who is usually on site for a test. The DLR test leader is the solely responsible party during a test on decisions of test continuation or stoppage based on the information provided to him by his team.

The team which performs the actual hot run test is named by the test leader and each member has a dedicated and clearly defined function in test preparation and execution. This is necessary in order to prevent misunderstandings and errors.

The key factor to ensure the success of a test is teamwork, especially during a test on a facility such as the P4.1 where more than 50 people are directly involved and need to be effectively co-ordinated.

4.6.3 Test Post-Processing

After the test an evaluation of bench data is performed by the DLR test facilities team while the evaluation of the test specimen data is done by the manufacturer of the test specimen himself. In case of unexpected behaviour of either the specimen or test bench - anomaly reports (NCR) are issued. In order to guarantee optimum performance of the next test all anomalies are treated (solved or accepted with justification) before the next test.

During a test campaign usually several tests are performed with one test specimen. The user defines the objectives for his test specimen in a separate document. This is used by DLR to prepare the test setup. The DLR teams are responsible for the test facility objectives and the definition of the test.

The campaign ends when the test specimen is removed from the test facility.
4.6.4 Safety Measures

High-energy rocket propellants are usually very reactive, therefore safety rules apply during all processes at the test facilities.

Storable propellants are carcinogenic and harmful pollutant and are treated accordingly. Specific safety measures which are always in effect include the following:

- The access to the facilities is only allowed to trained personnel. Visitors or untrained personnel have to be accompanied at any time by trained personnel. Access permission to the facilities can be granted by the department of test facilities only.
- Specific safety measures such as remote sensors for propellant detection are installed on the facilities as standard and are maintained and checked regularly.
- Activities for handling of storable propellants where personnel have to be present is only allowed with special personal protective gear which is also regularly checked, maintained and updated.
- For specific procedures such as e.g. tanking operations certain further restrictions do apply and are to be followed and documented.
- Communication between different test team members during special activities is ensured via an extensive intercom system. Additionally a public announcement system for the facilities is available.
- Each facility has certain safety relevant measurements directly connected to the central safety system. Via the integrated alarm information system it is ensured that problems can be treated quickly by the responsible test team.
- The design of the facilities includes safety measures (e.g. safety valves, burst disks) as standard equipment which are continuously verified and upgraded.
- Bench and engine control is conducted remotely from the command rooms and buildings which are protected against failure scenarios. Visual control is ensured by an extensive video system at each test facility.
- The staff of the DLR department of test facilities is trained regularly with respect to the aforementioned topics.

The high energy density at the running engine is a potential danger in itself. The possibility of a fault occurring causing considerable damage to the engine and its surroundings can not be completely ruled out.

It is forbidden for anyone to be in the vicinity of a running engine. Test procedures are organised in such a way that the test facility is cleared completely off personnel before being activated in preparation for a hot firing test. While the facility and engine undergo further preparation remotely for the hot firing test, the safety radius around the test facility is systematically extended.

During first access to the facility after the test, global leak detection is carried out along the supply lines and around the engine itself together with a first visual inspection by a small group of personnel.

4.7 New Developments, Configuration Management and Modifications of Test Facilities

Each test facility is designed, built and commissioned according to a certain specification and following a clearly defined procedure. This procedure is documented in detail and kept in the Integrated Management Handbook of DLR Lampoldshausen. The new development of a test facility is managed by the department of Engineering at DLR Lampoldshausen through the standard design phases till the Critical Design Review. Then the responsibility for erection and commissioning of the new facility is handed over gradually from the department of engineering to the department of test facilities internally at DLR Lampoldshausen.

One main goal is to perform the commissioning with the team which will operate the test facility in the future so that all know-how and experience can be preserved and used for the operational phase of the facility.

When the new test facility is finished and the commissioning is completed then the operational phase of the facility begins. During the operational phase modifications and adaptations of the facility also become necessary mainly due to changing test objectives or specimen hardware from the user side. Therefore a configuration and modification management system is in place at DLR Lampoldshausen.

The initial configuration of the facility is fixed by the as-built and commissioning status of the facility.
which is established and documented in a so-called CRE, or ‘Acceptance Review’, meeting.

Modifications to the facilities are performed with a so-called DMI process (DMI = Demande Modification Immédiatement). With this process it is ensured that each modification of a facility is planned, checked, performed and documented.

Each modification is identified by a numbering scheme and documented in specific form sheets. The modifications may vary from very minor up to very major modifications in the functionality of the test facility. Figure 4.7 shows an example of DMI performed for the P4.1 in 2010. Each modification is discussed and checked by a dedicated committee where decisions about financing, technical feasibility and realization of the modification are made. The committee consists usually of the DLR and the user and (if applicable) ESA as the economic owner of the test facility. The realization of the DMI is under the responsibility of the DLR department of test facilities.

Each DMI has to be documented in a certain way and the reception is checked by the establishment of so-called PV (Process Verbal, a specific protocol of acceptance).

In this DMI process one step is also the updating of the as-built and commissioning status document of the facility itself so that the current configuration is always known.

<table>
<thead>
<tr>
<th>DMI #</th>
<th>DMI Title</th>
<th>Accept. Status</th>
<th>Appl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4.1-05/1032</td>
<td>Increase of reliability of tank pressure regulation</td>
<td>Accepted</td>
<td>M3/M4</td>
</tr>
<tr>
<td>F4.1-06/1055</td>
<td>Displacement of bench IF of bench/engine flexible</td>
<td>Accepted</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-06/1065</td>
<td>Helium injection on feed lines (SIF F32 and F33)</td>
<td>Accepted</td>
<td>M3-06</td>
</tr>
<tr>
<td>F4.1-07/1092</td>
<td>Intake ring for adapter 22.3</td>
<td>Accepted</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-09/1112</td>
<td>Housing of diffuser and anti-corrosive protection system</td>
<td>Accepted</td>
<td>M3</td>
</tr>
<tr>
<td>F4.1-09/1115</td>
<td>GN2 service supply system for P4.1 maintenance</td>
<td>Accepted for study</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-09/1116</td>
<td>Installation of second water ring pump</td>
<td>Accepted</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-10/1118</td>
<td>Transverse load on MDD ball screw</td>
<td>Accepted for study</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-10/1119</td>
<td>P4.1 DIADEM Integration</td>
<td>Accepted for study</td>
<td>M4</td>
</tr>
<tr>
<td>F4.1-10/1120</td>
<td>Nozzle Extension Displacement Limitation Device</td>
<td>Accepted</td>
<td>M3-07</td>
</tr>
<tr>
<td>F4.1-10/1121</td>
<td>Modification NIG9553, ‘54, ‘56, ‘57</td>
<td>Accepted for study</td>
<td>-</td>
</tr>
<tr>
<td>F4.1-10/1122</td>
<td>Hot LH2 at Vinci pump inlet</td>
<td>Accepted for study</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-10/1124</td>
<td>Hoisting Devices for Long Nozzle (eps = 243) Integartion</td>
<td>Accepted</td>
<td>M3-07</td>
</tr>
<tr>
<td>F4.1-10/1125</td>
<td>Installation of Background/Screen for BOS in P4.1 Vacuum Chamber</td>
<td>Open</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-10/1126</td>
<td>Modification of Flow Meter Channels</td>
<td>Accepted</td>
<td>M3-06</td>
</tr>
<tr>
<td>F4.1-10/1131</td>
<td>Rigid line on spectrometer line for chamber and VCO VCH leak detection</td>
<td>Open</td>
<td>M3-08</td>
</tr>
<tr>
<td>F4.1-10/1132</td>
<td>Pressure measurement in diffuser center body</td>
<td>Open</td>
<td>TBD</td>
</tr>
<tr>
<td>F4.1-10/1133</td>
<td>Additional manual valve on H2 tap-off circuit</td>
<td>Open</td>
<td>M3-08</td>
</tr>
</tbody>
</table>

Figure 4.7: List of DMI applicable for P4.1 in 2010
4.8 Maintenance

One main point in order to keep the facilities in operational conditions over a long period of time is the maintenance. Maintenance plans exist for each facility. They are reviewed periodically and updated in case of modifications to the facilities. The maintenance is performed by the same team which also operates the facility.

4.8.1 Maintenance Philosophy

The maintenance includes all technical, management and administrative actions, which are performed in order to guarantee the nominal status of the test facilities with respect to their technical installations and associated support systems.

The technical installations of the test and supply facilities basically comprise

- the facility with all its necessary equipment and supply systems
- the security system
- the data acquisition and control systems

With respect to the test and maintenance activities the benches and supply facilities are in a different status: operational, active waking, cocooning or stopped (see also chapter 4.2).

The nominal maintenance means all activities required to maintain the facility in an operational status during test campaigns.

A test campaign is sometimes interrupted by a yearly maintenance phase for a delay no longer than 6 weeks, if main systems (e.g. measurement and control systems) have to be maintained. During the phase of yearly maintenance the facility becomes non operational, meaning no activities for engine testing are possible.

In case of a larger break in the usage of a facility between two test campaigns, reduced maintenance following a run down phase may be performed. Reduced maintenance, also called “basic maintenance” covers all activities for maintaining the facility in a predefined status (e.g. active waking or cocooning).

Different kinds of maintenance actions for the conservation and restoration during the lifecycle of technical equipment exist:

- Preventive maintenance (i.e. regularly at a certain cycle), subdivided in conditional and systematic maintenance. This type of maintenance is conducted to keep equipment working and/or extend the lifetime of the equipment.
- Continuous maintenance (i.e. during normal working process).
- Corrective maintenance, subdivided in palliative and curative corrective maintenance. This type of maintenance could be a repair or an exchange of equipment and is conducted to get equipment back into working order.

All these kinds of maintenance actions can be grouped in the following five levels:

- 1st level maintenance covers simple actions, which are necessary to the normal running of the system as daily greasing, purging of filter elements or inspection rounds to verify condition and proper function
- 2nd level maintenance covers easy-to-perform actions which require simple procedures and/or utilisation of support equipment and which is carried out by qualified (trained) personnel
- 3rd level maintenance covers complex actions such as checks, adjustments or troubleshooting, using portable support equipment or measuring equipment which is carried out by qualified technicians
- 4th level maintenance covers operations demanding a good knowledge of a particular technique/technology, for example vibration analysis, replacement of a compressor check valve or servicing of a pump in a specialised workshop
- 5th level maintenance is defined as the renovation or reconstruction carried out by the manufacturer or a specialist company.

Those responsible for maintenance are concerned with:

- Management of objectives, best strategy
- Team organization
- Choice between preventive vs. corrective maintenance, systematic or conditional maintenance
- Coordination and harmonization of all relevant maintenance activities
- Detailed planning
- Decision of in-house or subcontracted external maintenance
- Guarantee of respect of quality assurance
NCR analysis and consequences
Application of the technical standards and rules
Internal and external reporting
Application of lessons learned.

Each system or part of a facility is composed of a certain number of subsystems and/or elements for which maintenance actions are defined. These actions take into account manufacturer’s recommendations and feedback from the operational team and constitute a part of the maintenance activities. All operations of maintenance activities are assisted by an in-house software maintenance tool, developed by the department of test facilities. The software package provides assistance for the following tasks:

- planning operations
- managing execution of events
- management of assets (parts, tools, equipment, inventories).

The software also serves as a knowledge database on:

- Maintenance service history
- Reliability data: MTBF (mean time before failure), MTTB (mean time to breakdown), MTBR (mean time between removals)
- Maintenance and repair documentation and best practices
- Warranty/guarantee documents.

### 4.8.2 Maintenance Plans and Reports

All maintenance plans and periodical reports of the facilities are based on DIN norms, VDI principles, special rules (e.g. AD notice sheets; pressure bottle rules (AD – Arbeitsgemeinschaft Druckbehälter); UVV (Unfallverhütungsvorschriften); installations to be examined as well as instructions by the manufacturer as well as on the experience in maintaining the systems.

The maintenance plans are divided into four sections according to the function of the different systems (abbreviations in French):

- EMSF: mechanical equipment fluid system
- EMCR: mechanical equipment control and direction systems
- BGCI: general buildings and infrastructure
- MGT: general technical means

These sections are subdivided into their special systems and subsystems respectively depending on the facility.

In each section catalogue sheets of maintenance actions for each subsystem are structured where an identification number as well as the description of the type of activity and the regular execution cycle are defined.

The different maintenance actions are executed over the year, and at least the actions of continuous maintenance have to be integrated into the normal working process to keep the main systems in a permanent standby-for-activation mode. The instructions for these actions are reference-time schedules; the real-time maintenance actions are adapted to the actual activities at the test facility.

The periodical maintenance report of a facility is based on the maintenance plan of the respective facility and consists of general remarks about the relevant period, a detailed checklist of the maintenance actions and their calendar as well as chapters dealing with the NCR treatment.

### 4.8.3 Spare Parts and Consumables

Beyond special equipment and tools, spare parts and consumables are items, which are necessary to perform the maintenance actions.

Optimal spare parts provisioning is a prerequisite for all types of maintenance tasks such as inspections, preventive maintenance and repairs. With the exception of preventive activities spare parts for maintenance tasks are usually required at random intervals. Thus, the fast and secure coordination of the demand for spare parts with the supply of them at the required time is an important factor for the punctual execution of the maintenance process.

Spare parts management and an organized store-room is one of the key processes which support effective maintenance planning and scheduling and equipment reliability improvement.

For the management and organisation of the spare parts and consumables, the department of test facilities has developed a software tool “LVP” (= Lagerverwaltungsprogramm), which performs the following tasks:

- Database for spare parts and consumables including definition of minimum number of assets with automatic reminder
• spare parts and consumables planning operations
• managing execution of events such as ordering assistance
• management of assets (parts, tools, equipment inventories)
• database on spare parts and consumables history
• database on serial numbered parts
• support of maintenance and repair documentation and best practices
• reference for warranty/guarantee documents.
Thus all relevant parties have complete insight into material availability. The material withdrawals are documented and form the basis of usage-controlled materials planning. With this process, material stocks of spare parts and consumables can be optimized to support maximum availability with minimum stocks.

For the ESA test benches and supply facilities the common storage area for spare parts and consumables is in general in building M29.

Common consumables such as oil, grease, etc. for the test facilities are standardised in order to limit procurement and storage costs and to minimise the risk of passing their expiry date.

4.9 Renewals / Upgrades

The test facilities and associated support systems need to be operated for a long period of time. In this time not only the technical know-how is changing but also legal requirements may change. The so called renewals and upgrades program for the facilities is in place in order to provide the department of test facilities.

An upgrade of a system, subsystem or piece of equipment becomes necessary when statutory or legal regulations change.

A renewal of a system, subsystem or piece of equipment becomes necessary when

• The item cannot be maintained any more due to its obsolescence or the obsolescence of its main component parts (i.e.: no longer procurable).
• The item cannot be maintained any longer due to the fact that the sole supplier ceases operations
• The operating and maintenance costs become so high (e.g. due to necessary repairs) that its use is no longer cost-effective.

<table>
<thead>
<tr>
<th>WP Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 100</td>
<td>Fire protection measures (part 1)</td>
</tr>
<tr>
<td>21 200</td>
<td>Lightning protection measures (part 1)</td>
</tr>
<tr>
<td>21 300</td>
<td>Security LH2 discharge</td>
</tr>
<tr>
<td>24 100</td>
<td>P4.2 adaptation of cooling machines</td>
</tr>
<tr>
<td>31 100</td>
<td>Replacement of LH2 pilot tank (part 1)</td>
</tr>
<tr>
<td>31 200</td>
<td>Renewal of intercom system</td>
</tr>
<tr>
<td>31 300</td>
<td>Renewal of gas analysis system</td>
</tr>
<tr>
<td>31 400</td>
<td>Installation of pre-softening system</td>
</tr>
<tr>
<td>31 500</td>
<td>Refurbishment of air supply M7-E24</td>
</tr>
<tr>
<td>33 100</td>
<td>P3, Renewal of RVCU</td>
</tr>
<tr>
<td>33 200</td>
<td>Transfer of P3 MCC system</td>
</tr>
<tr>
<td>33 300</td>
<td>P3, renewal of sensors</td>
</tr>
<tr>
<td>33 400</td>
<td>Refurbishment of building P3</td>
</tr>
<tr>
<td>33 500</td>
<td>P3, renewal of ESS</td>
</tr>
<tr>
<td>34 100</td>
<td>Renewal of water sluice valves</td>
</tr>
<tr>
<td>34 200</td>
<td>Renewal of decontamination system</td>
</tr>
<tr>
<td>34 300</td>
<td>P4 Refurbishment of crane</td>
</tr>
<tr>
<td>34 400</td>
<td>Improvement of cooling water supply</td>
</tr>
<tr>
<td>34 500</td>
<td>Dynaworks Licences Upgrade</td>
</tr>
<tr>
<td>35 100</td>
<td>PS LOX bench line re-installation</td>
</tr>
<tr>
<td>35 200</td>
<td>PS Study civil works refurbishment</td>
</tr>
<tr>
<td>35 300</td>
<td>PS Refurbishment of the roof</td>
</tr>
<tr>
<td>35 400</td>
<td>PS Refurbishment of guide tube and deflector</td>
</tr>
<tr>
<td>35 500</td>
<td>Renewal of SSHeL</td>
</tr>
<tr>
<td>35 600</td>
<td>PS Renewal of ASS and ASM</td>
</tr>
<tr>
<td>35 700</td>
<td>GN2 pressurisation line LOx runtank</td>
</tr>
</tbody>
</table>

Figure 4.8: Listing of Renewals and Upgrades foreseen to be performed on ESA facilities at DLR Lampoldshausen in the time frame 2011 up to 2013

In Figure 4.8 it is shown which renewals and upgrades are foreseen in the period of 2011 to 2013 on various ESA facilities.
In order to identify possible and necessary Upgrades and Renewals the following data sources are available:

- Database of laws and regulations applicable for DLR Lampoldshausen in IMH
- Information from authorities about changes in laws and regulations
- Risk analysis or technical studies including evaluation of MTBF (mean time before failure) and determination of the criticality of the equipment
- Information from suppliers and manufacturers
- Results of internal and external audits
- Results from NCR treatment and performance of maintenance activities
- Information about the life time and use of the equipment, life cycle of the equipment
- Evaluation of costs and cost factors.

The selection method for defining and prioritizing the upgrades and renewals takes into account the following criteria:

- the probability of failure of the equipment in the near future
- the age of the equipment
- the possible influence on testing activities
- the total costs for the new equipment
- the non-availability of the equipment in the last year
- the due date and the urgency of the realization of an Upgrade with respect to legal regulations
- the time needed to design, manufacture, install and accept a new equipment.

4.10 Data Acquisition, Measurements, Test Control

4.10.1 Measurement, Command and Control Systems (MCC)

Test facilities have an integrated system for data and measurement acquisition, measurement conditioning, data treatment and control of the test benches in preparation phases and during hot firing tests. These so-called MCC systems are a very important part of test operations as they are the means with which control over the bench and the test specimen during the hot fire test phase is achieved. Today the necessary short reaction times and complex sequence structures can only be realized with real-time computer systems.

On the test facilities P1.0, P3.2, P4.1, P4.2 and P4DE as well as on P8 computer systems from the French company Eurol ogic are in use. On the test facilities P5 and P6.1 computer systems from the German company Werum are in use. The system which is used to operate the supply facilities (UMS – Utility Management System) is a Siemens WinCC System. This is the only system which was not specifically developed for the purpose of controlling a hot run test facility but is a standard system with adapted programming.

One main aspect of the test bench systems, used for controlling a hot run, is the safety. Each test facility MCC system has a specifically adapted safety logic which is defined, established and tested by the test team.

Despite the use of different computer systems there are also common rules and functions which are respected at all the test facilities for the MCC systems:

- Each system needs to have at least one back-up system (ESS – Emergency Stop System) in case of failure
- The system needs to monitor itself so that the automatic triggering of the Emergency Stop System (Watchdog) is enabled
- The system needs to perform data and event acquisition and archiving during hot run test and if needed during functional checks
- The system needs to perform high-frequency acquisition and archiving during hot run test
- The system needs to perform limit value monitoring of critical data and events during hot run test and if needed during functional checks
- The system needs to control test procedures with automatic pre-defined sequences. For this the system automatically gives commands to the actuators (e.g. valves) of the test facility and the test specimen in a stipulated time sequence. These commands can be both digital (for automatic valves) and analogue (for regulation valves).
- The test preparation is done with entry of parameters and programming of test environments via the process terminals. The system
needs to allow fast and easy programming and verification of programming during test preparation as each test has usually a different set of pre-defined sequences

- The system needs to perform the regulation of important dynamic variables (e.g. mass flow)
- The simulation of test facility procedures during test preparation needs to be possible
- The system has to perform a safe test shut-down in the event of abnormal test facility or test specimen behaviour
- The system needs to allow manual user communication via graphic process terminals. The graphic synoptics are defined by the test team for each test facility and need to be adaptive.
- The system needs to allow immediate evaluation of tests and suitable presentation of data/events after tests via process terminals
- The long-term archiving and management of test data needs to be ensured
- Test data transfer has to be possible to a computer system which the manufacturer of the test specimen uses to analyse the test specimen data.

The latest major development of MCC systems was done at the P5 where the 20 year old Norsk Data Computer System was replaced with a new system designed and built by a consortium of three companies (German company Werum, Belgian company Cegelec, German company SEA) under the leadership of Werum and following detailed technical specifications by DLR. The new system went into operation in 2010 after extensive testing and performed successfully during the first hot firing campaign with a Vulcain 2 ARTA engine.

4.10.2 Measurements

As a general rule, the measurement channels at the test facilities consist of the electromechanical transducer at the measuring site and signal conditioning at the standardised input (typically -- 10 V) to the data acquisition system. The transducers are wired to the signal conditioning units and the signal conditioning units are wired to the data acquisition (MCC) system.

In the special case of so-called transmitter measurement channels, the sensors and signal conditioning circuits are grouped together at the measuring side.

Shunt distributors are frequently inserted in the cable connections to allow for flexible adjustment to operating requirements.

The number of measurement channels being managed varies from more than 1000 at test facility P4.1 to less than 100 at test facility P1.0.

Depending on the facility concept, the length of wiring between transducer and signal conditioning unit can vary.

- In the centralised concept (e.g. P3.2, P5), the signal conditioning units are installed together with the data acquisition equipment centrally in the control building. This requires cable lengths of up to approx. 400 m.
- In the decentralised concept (e.g. P8, P4) the signal conditioning units and data acquisition equipment are erected locally in the test facility itself. Here the average cable length is only approx. 20 m.

The decentralised system of acquisition and archiving offers considerable advantages in measurement quality, in minimising cable requirements and in the flexibility of topological system arrangement, such that this version is generally given preference when new systems are being designed.

The transducer and signal conditioning units are the most vulnerable elements in the measuring channels and require the most attention. Regular readjustment of the signals is necessary because of the frequently changing measurement ranges and also because of stability issues. These adjustments are made normally by computer via the setting of relevant parameters for the signal conditioning units.
For each measurement a set of calibration parameters is stored in the MCC database. These are used to calculate the physical values of each particular measurement variable in real time and give a feedback to the operator during test preparation and during testing.

Basically there are two different types of data acquisition:
- Low-frequency data acquisition
- High-frequency data acquisition.

Low-frequency data are measured signals in the frequency range up to approximately 1000 Hz. High-frequency data are generally measured signals with a nominal frequency of more than 1000 Hz. Special wide-band amplifiers are used to condition these HF signals to the inputs of the acquisition equipment. Additional RMS channels filter the HF measurement channels in the LF band and thus enable archiving and evaluation in the low-frequency data acquisition system.

Correct acquisition of all the frequencies requires higher scanning rates in the analogue / digital converters. However, to avoid unnecessarily high scanning rates where slow signals are concerned (e.g. temperatures), the rates can be reduced in several stages down to approximately 1 Hz for LF acquisition and to approximately 1000 Hz for HF.

In order to eliminate the aliasing effect which can create interference in such cases multi-pole filters are used with a limit frequency just above the highest effective frequency.

Both, the LF and HF data acquisition are done via the MCC system. The advantage of such direct computer recording is that low and high-frequency data can be integrated in the same computer environment and processed with the same evaluation package. Where large quantities of archived data are concerned, compression procedures are very important for rapid analysis of the recordings. These are implemented as software in the computer systems.

All parameters required for this kind of data acquisition are defined by the measurement engineer, stored in the databases and documented in the respective test documentation.

In the centralised acquisition system, the measured signals are transferred after digitisation via the DMA channel to the central computer and stored there on the one hand for real-time presentation (process pictures) and on the other hand for archiving on the disk of the background computer system.

In the decentralized acquisition, the measured signals are stored after digitisation on a disk in the (local) front-end computer; the measuring channels required for real-time presentation (process pictures) are transferred in real-time via a suitable bus system (Ethernet or reflective memory) to the central back-end system.

One important topic of the regularly preventive maintenance to be done on the measurement equipment is to perform the calibration of the measurement transducers. At DLR Lampoldshausen there is a calibration laboratory available which is able to perform the calibration of pressure, differential pressure and temperature transducers, transmitters and gauges. This laboratory is under the responsibility of the department of Engineering and works closely with the test facility teams. As the calibration for temperature measurement equipment can only be done in a limited temperature range there is also a cryogenic calibration system which is under the responsibility of the department of rocket propulsion.

For the performance of maintenance activities on the conditioning units, specific tools and test racks are available so that preventive maintenance as well as the diagnosis of problems can be done directly by the test team at the test facility itself.

4.10.3 Test data

All test data for the test facilities has to be stored for a minimum of 10 years. This is done today by specific data storage systems (NAS – Network Attached Storage). The test data evaluation is nominally done by the test team with the so-called DynaWorks software which is a standard software package made by the company Intespace. The test team of DLR evaluates the data of the test facilities in detail.

After a test, the test data of the test specimen is transferred via secured lines to the user for further assessment. The evaluation of the test data is done in two ways
- Standard evaluation after hot fire test
- Detailed evaluation of specific areas or problems arising during standard evaluation or testing.

For the standard evaluation a pre-defined set of diagrams is created automatically for fast evaluation by the test team. The results are used as input for the preparation of the next test. In case of problems, anomaly reports (NCR – Non Conformance
Reports) are opened and more detailed investigations are started.

In order to be able to perform the above mentioned functions, test data management is necessary. Those responsible for test data management are required to ensure:

- the integrity of the test data available on-line and in the archives
- reliable storage and reproduction of archived test data.

The integrity of test data is guaranteed by available automatic procedures for:

- automatic transfer of test data from the acquisition system to the archiving system
- automatic transfer of other essential test-specific data and programs such as test databases, sequences, regulation programs and simulation programs into the archiving system.

### 4.11 High Altitude Simulation Facilities

The engines that are installed in rocket upper stages, satellites or space probes all operate at high altitudes above ground, i.e. under ambient conditions in which vacuum prevails. This affects the ignition of the engines because the fuel conditioning process in a vacuum is not the same as on the ground. Engines develop more thrust and are thus exposed to greater stresses and strains. Moreover, the physical laws that govern thermal balance are different from those on the ground, because heat cannot travel through a vacuum by convection. To simulate these conditions exactly, vacuum test facilities are needed which, like P4, are capable of creating an environment with an atmospheric pressure of only a few millibars (mbar) while the engine is running.

The German Aerospace Center at Lampoldshausen operates a variety of vacuum test facilities. P1.0, for example, is used to test satellite engines with a thrust of up to 600 Newton (N). Tests on the current upper stage engine of the launcher Ariane 5 are conducted on P4.2. The engine, called AESTUS, generates 27.5 kilo-Newton (kN) of thrust. The future upper-stage motor of Ariane 5, Vinci, with a thrust of 180kN is being tested on P4.1.

The know-how of designing and operating these kinds of facilities is a core competence of the DLR Institute of Space Propulsion in Lampoldshausen.

Over 50 years the DLR has systematically extended its know-how in this respect, gathering experience in the relevant fields of technology, and is therefore today essential for all development and qualification programs of space engines in Europe.
5. Test Facilities

5.1 Supply Facilities

5.1.1 Operation of Supply Facilities

The supply facilities - cryogenic and gaseous supply facilities as well as the cooling water supply facilities - are operated in a close co-operation with the external company Air Liquide Deutschland ALD. The overall responsibility and management of the facilities lies with the DLR department of test facilities. In order to harmonize supply operations with overall testing activities as well as modification and maintenance actions on the supply facilities themselves, there is a dedicated officer (as well as a deputy) within the department of test facilities to act as the direct interface between ALD and the department of test facilities.

Regular meetings are held for planning supply operations as well as to address technical issues and problems.

5.1.2 Cryogenic Supply

During the installation phase of the test facility P5 new propellant and gas supply systems were also installed. Between 1988 and 1990 two tank depots for liquid hydrogen (T58) and liquid oxygen (T23) were erected on the test site. Both systems are jointly controlled and monitored from control building G56.

T58 depot not only supplies test facility P5 with liquid hydrogen but also P4.1. T23 supplies P5 with liquid oxygen, as P4.1 has its own oxygen supply located at the P4 Steam Generator plant.

The hydrogen depot T58 consists of the following elements:

- Main storage tank, vacuum-insulated, 270 m³ capacity, storage temperature 20 K
- Pilot tank, vacuum-insulated, 55 m³ capacity
- Two connections for tank vehicles
- Pressurisation system
- Transfer line to P5 and transfer line (connected to P5 line) to P4.1
- Safety equipment.

The extremely cold (20 K) liquid hydrogen is delivered by trailers with a capacity of up to 50 m³. Two vehicles can be discharged at the same time. An amount of approximately 200 m³ liquid hydrogen can be delivered in one day.

The hydrogen from the storage tank is conveyed in the preparation phases between the tests through the transfer lines (approx. 350 m to P5 and approx. 500 m to P4.1) to the run tanks at the respective facility.

These flexible, vacuum-insulated lines facilitate safe transfer of the hydrogen to the test facilities at a transfer rate of about 100 m³ per hour.

Together with the test facility equipments on P4.1, P5 and P3.2 it can be said that the DLR site in Lampoldshausen contains one of the largest liquid hydrogen infrastructures in Europe.

Figure 5.1: LH2 storage area T58

Figure 5.2: LOX storage area T23

Similar to the hydrogen depot the liquid oxygen depot consists of the following elements:

- Vacuum-insulated storage tank with 210 m³ capacity, storage temperature 90 K
- Two connections for tank vehicles
• Pressurisation system
• Transfer line to P5
• Safety equipment.

Oxygen is delivered in suitable trailers with a capacity of 15 m³ per vehicle.

The oxygen is transferred from the storage tank via a 250 m long transfer line to the run tank of the test facility P5. The transfer line is of the same design as the hydrogen transfer line to the P5 with a transfer rate of up to 40 m³ per hour.

The LOX storage tank is pressurized before transfer by regulated evaporation of liquid oxygen in the adjoining heat exchanger.

Both depots are in operation since 1990. Throughout this period around 90,000,000 Nm³ (normed cubic meters) liquid hydrogen and around 32,000,000 Nm³ liquid oxygen have been handled for the supply of the facilities. More than 6,400 trailers with liquid hydrogen and liquid oxygen have been unloaded during this time: an impressive illustration of the safe handling procedures of these installations.

5.1.3 Conventional Propellant Depots

Depot T16

The acid depot T16, consisting of T16-A and T16-B, was used in former times for the storage of concentrated nitric acid (HNO₃) which was used at the facilities P1, P2 and P4.

Nowadays the depot is used as a backup storage area in case of either problems with the facilities’ own supply systems or shortage of available storage capacity. In this respect the T16 is considered part of the operational infrastructure of these facilities.

T16 is built on a collector basin which prevents the dangerous liquids from polluting the environment in the event of a leak. There is also a sprinkler system installed to precipitate any vapour or dilute any leaks. The resulting acid water is conveyed to the decontamination system.

Depot T18

The fuel depot T18 consists of

• 6 storage tanks with a capacity of 4 m³ each for diesel, turpentine and heating oil
• One storage tank with a capacity of 32 m³, divided into three separate chambers for kerosene.

The depot is used generally for the storage of the aforementioned liquids and is also equipped with measures to prevent the liquids flowing free in case of a leak.

Depot T21

The depot T21 is used for monomethylhydrazine (MMH) backup storage much in a similar way as described before at the T16 depot.

Depot T13

The depot for solid fuels T13 was erected together with the P5 test facility. The Vulcain engines in this test facility are started using three different pyrotechnic igniters. The prescribed storage of these igniters is in this special blockhouse facility which was built especially for this kind of material and certified accordingly by the authorities.

It is adjoined to an air-conditioning chamber which can be adjusted for a broad range of temperature and humidity conditions for the storage and examination of solid fuels.

This installation is subject to constant safety monitoring. Only specially trained staff are allowed to enter the depot and handle the igniters. Furthermore, only authorised companies are allowed to transport and deliver the igniters.

5.1.4 Gaseous Supply

Operation of the test facilities requires an adequate supply of the gases hydrogen (GH₂), helium (GHe) and nitrogen (GN₂) under various pressure levels.

The corresponding equipment is located in the upper section of the test site and consists of the compressor station D57 and the nitrogen installation D22, operated from the control building G56.

Figure 5.3: Control Building for Supply Facilities G56
Supply of Gaseous Hydrogen

The hydrogen compressor station D57 consists of:

- Three membrane compressors for outlet pressures of up to 320 bar for possible flow rates of 175 Nm³ per hour.
- Two membrane compressors for outlet pressures of up to 800 bar for possible flow rates of 175 Nm³ per hour.

D57 has connections to the following installations:

- Test facility P5, five pressure tanks with a capacity of 8 m³ each for max. 320 bar.
- Test facility P4.1, five pressure tanks with a capacity of 8 m³ each for max. 320 bar.
- Test facility P3.2, two pressure tanks with a capacity of 15 m³ each for max. 800 bar and two pressure tanks with a capacity of 4 m³ each for 320 bar.
- Test facility P8, one pressure tank with a capacity of 6,5 m³ for max. 630 bar.
- One pressure tank with a capacity of 4 m³ for max. 320 bar near the compressor station itself as a buffer tank.

Before compression the hydrogen gas is withdrawn either from a gas storage system consisting of 2 tanks (100 m³ with 25 bar and 50 m³ with 40 bar) or from the pilot tank in the liquid hydrogen depot. The suction pressures for the compressors lie between 2 and 6 bar.

Supply of Gaseous Nitrogen

Installations for generating nitrogen gas are grouped together at building D22. Two vacuum-insulated tanks each with a capacity of 33 m³ store the nitrogen which is delivered in liquid form.

The gaseous nitrogen produced at D22 is delivered to the following consumers:

- Test facilities P1 and P2 (200 bar).
- Test facilities P5, P4 (P4.1, P4.2 and P4 steam generator) and P3.2 with their supply systems (320 bar).
- Test facilities P3.2 and P8 (800 bar).

An additional 200 bar network supplies gaseous nitrogen to various consumers across the site (e.g. laboratories and workshops).

The original system for generating nitrogen gas went into operation together with the test facility P5. In 2010, after more than 20 years operation, the system was renewed under an ESA contract. The renewal was necessary as the operation and maintenance costs increased steadily together with the tendency of failures of the system. Furthermore certain spare parts were no longer available on the market and the system was therefore obsolete.
The renewal of the D22 system has been carried out without major interruptions to the supply of GN2. The project was split up into coordinated steps in order to keep the existing facility in operation as long as possible. In parallel the new system was provisionally placed on a separate location. After procurement, erection and commissioning on the provisional site, the new pumps and evaporators were connected to the GN2-pipe network and have taken over supply from the old system. Subsequently the old system was dismantled and the interior of building D22 was renovated. The final action was then the transfer of new pumps from the provisional site to the original facility location.

The new system now supplies the 200 bar network via four pumps, as opposed to the old system which only had a single pump.

The new gaseous nitrogen production station D22 consists of

- two LIN – Pumps at 320 bar
- two LIN – Pumps at 800 bar
- one air heated high pressure vaporizer at 420 bar
- one air heated high pressure vaporizer at 840 bar
- other assets like high pressure valves, pressure reducers, safety valves, instrumentation such as pressure and temperature sensors.

Supply of Gaseous Helium

A membrane compressor (230 bar, 175 m³ per hour) supplies helium gas to P5, P4.1 and P4.2.

The helium is taken from a bottle transport delivery vehicle which is regularly exchanged.

5.1.5 Cooling Water Supply

Large test facilities such as the P4.1 require supply of over 4.200 litres per second of cooling water during testing. This massive consumption is supplied by reservoirs.

The first stage in development of the cooling water supply system for the test site began with the erection of the large-scale test facilities P3 and P4 and included:

- a tank with a capacity of 1.000 m³ in the upper part of the site (N33)
- a pipeline system with pipes of 1 m diameter with shut-off valves and control shafts for supply to P3 and P4
- an underground water reservoir system below the test facilities P3 and P4 with a capacity of 1.400 m³.

It then became necessary to extend the water supply system at the start of the Ariane 5 project with the erection of the P5 facility and the modification of the P4.2 test facility. The following elements were added to the system while the original components remained in operation:

- another tank with a capacity of 1.000 m³ (N63) next to the first tank
- branches and extensions to the pipeline system through to test facility P5
- replacement of the water cooling system for the existing tank N33 so that the water which has been warmed up in test facility P4.2 can be again cooled down to temperatures of around 5°C.

With the erection of the test facility P4.1 another extension of the cooling water supply system became necessary. The following elements were added while all the above mentioned ones still stayed in operation:

- another tank with a capacity of 4.000 m³ (N63A) next to the two aforementioned tanks
- branches and extensions to the existing pipeline system (diameter 1 m) to test facility P4.1
- integration of another pipeline system from the new water tank N63A to the P4.1 condenser with a diameter of 1,2 m including shut-off valves and control shafts
- integration of another underground water reservoir system below the test facility P4 next to the old underground water reservoir with a capacity of 4.800 m³
- integration of another water cooling system which is able to cool down all the water tanks but especially the new one N63A to temperatures of around 5°C
- integration of another cooling system which is able to cool down all the water tanks but especially the new one N63A to temperatures of around 5°C
- integration of a water softening plant able to reduce the water hardness from about 35°dH down to about 7°dH which is necessary for supplying the P4.1
- integration of a filtering and biocide plant in order to remove organic or other pollution.
During tests the water flows through the underground pipelines from the tanks to the test facilities. The location of the tanks above the test facilities results in hydrostatic pressures which are sufficient for most cooling tasks without the need for additional pumps. If necessary the test facilities themselves use dedicated water pumps for specific cooling applications.

The remaining cooling water in the concrete basin of test facility P5 or the warmed cooling water from the underground water reservoirs is pumped back into the tanks through a separate pipe at the end of a test. During the preparation phases between tests the tanks N33, N63 and N63A are re-filled if necessary with water from a local deep well.

### 5.1.6 Decontamination Plant N39

Toxic propellants are used at test facilities P1, P2 and P4.2. These are hydrazine and monomethylhydrazine (MMH) as fuel together with dinitrogen tetroxide (N2O4) as oxidizer.

When handling these substances it is unavoidable for remnants to find their way into the waste water stream. All waste water from test facilities P1, P2, P4.2 and from tank depots T16, T18, T19, T20 and T21 is conveyed to the decontamination plant N39. All precipitation water in the vicinity of these tank depots and test facilities is also considered as possibly contaminated water.

The toxic nature of the aforementioned propellants makes it necessary for the water to be treated and purified before it leaves the test site.

The decontamination plant was renewed in 1998 in order to reduce the operational and maintenance costs and to regain a state-of-the-art technology level.

It was decided to install a system using catalytic water oxidation with hydrogen peroxide and ultraviolet light. In this process a hydrogen peroxide solution is treated with UV radiation so that OH radicals are separated. These radicals have a very high potential for oxidation and react with the substances to be removed.

The system is able to treat water which is contaminated with:

- Hydrazine / Monomethylhydrazine
- Dinitrogen Tetroxide
- Cyanide
- Nitrite
- Ammoniac
- Alcohols.

The advantages of this process are a high quality of the treated water, low rate of failures due to basic reactor technology, low requirements for personnel and good potential of extension.
Although the decontamination plant operates automatically, samples of the water discharged from the plant are taken daily for testing, in order to ensure that no unacceptable substances are discharged with the waste water and also to check regularly that the plant is functioning efficiently. Unannounced sampling is also conducted at irregular intervals by the responsible authorities to check compliance with the prescribed limit values.

**SOWARLA**

The conventional process of decontamination as described above needs certain amounts of energy and chemical substances. Therefore a demonstration plant for the purification of water using solar light and photo-catalysts was developed. This project was created following the initiative of the Technology Transfer Centre Lampoldshausen (TTZ), the German Aerospace Center (DLR) and the two local companies KACO new energy GmbH and Hirschmann Laborgeräte GmbH & Co. KG. The project was called SOWARLA (Solare Wasserreinigung Lampoldshausen). The demonstration plant has been in operation since 2010.

The main feature of the solar water treatment plant is the new receiver-reactor technology. This technology is based on patented solar modules with robust and highly transparent glass pipes.

The polluted water is mixed with photo-catalysts and oxidants, charged into the receiver and exposed to the sun until purification is complete. The water is then removed from the receiver, the photo-catalyst is separated and the purified water can be disposed of or re-used.
5.1.7 Workshops, Assembly Buildings and Spare Parts Storage

The test facilities department maintains several workshops, located both on the test facilities themselves and separate, stand-alone workshops. These are necessary particularly for maintenance work, minor repairs and modifications. Major work is usually contracted out to external companies.

Figure 5.11: Assembly Buildings M9 and M29

Two assembly buildings are available, M9 and M29. Building M29 has been built specially for work on the Vulcain engine and also accommodates the extensive stock of spare parts for the ESA test facilities and supply systems. Building M9 was used for work on the Viking engine and is used today to store spare parts and tools for the test facilities, as well as housing clean rooms and a laboratory for decontamination of small parts which have been in contact with toxic propellants.

5.2 Test Facility P1.0 and Control Building M6

5.2.1 Background

Engines of upper stages, satellites and space probes are ignited under very low ambient pressure or vacuum conditions. Therefore the propellant injection process is very different to that under sea-level conditions. In addition the engine has a higher thrust and power output while operating in vacuum and the thermal conditions are subject to different physical principles. In order to realistically simulate all these conditions for engine tests, high-altitude test facilities with the ability to keep air pressure as low as a few millibars are essential.

In the early 1960s the high-altitude test facility P1.5 was built at the P1 test facility complex within the frame of the ELDO program. It was the first facility of its kind at the DLR Lampoldshausen. The test facility was modified in 1978/79 for the development of the propulsion system for the Jupiter probe Galileo.

As technology evolved it became necessary to build a new high-altitude test facility. It was decided to develop P1.0 into a high altitude test facility which would replace the old P1.5. A new rocket steam generator with a mass flow rate of 10 kg/s using alcohol and liquid oxygen as so-called green propellants was put into operation. At P1.0 it is possible to test satellite engines with a thrust of up to 600 N. Test durations of about two hours are possible with an ambient pressure within the vacuum chamber below 2 mbar.

The first hot run of the steam generator took place in January 1999.

5.2.2 Characteristics of the Facility

The main procedure for a high-altitude simulation test on P1.0 can be described as follows:

- The vacuum chamber with engine, supersonic diffuser and exhaust cooler are evacuated up to a shut-off valve by means of mechanical pumps.
- The steam generator for the first and second ejector stages starts up consecutively. Once a corresponding pressure has been reached, the shut-off valve is opened.
- The auxiliary nozzle is started up and ignition conditions prevail.
- The engine can now be ignited several times. Differences in pressure before and after ignition are only slight, varying by 2 to 3 millibars.
The exhaust is sucked away in two stages by means of ejectors.

After the engine has been shut off, the auxiliary nozzle is shut down. To reduce back-flow into the altitude chamber, it is purged with a small amount of nitrogen.

Once the shut-off valve has been closed, the steam generators are switched off. The vacuum can be sustained for a while longer using the mechanical pumps.

The exhaust is sucked away in two stages by means of ejectors.

After the engine has been shut off, the auxiliary nozzle is shut down. To reduce back-flow into the altitude chamber, it is purged with a small amount of nitrogen.

Once the shut-off valve has been closed, the steam generators are switched off. The vacuum can be sustained for a while longer using the mechanical pumps.

The volume of the vacuum chamber is about 4.5 m³ and the achievable vacuum is around 10⁻¹ mbar.

Due to the hot exhaust gases coming from the apogee engine, the cooling of the high altitude simulation system is necessary. The hot gas cooler has a cooling capacity of 1.400 kW and has to sustain an inlet temperature of about 1.280 °C. The outlet temperature of the hot gas cooler is about 80 °C. The necessary cooling water is supplied via a pump at a pressure of 5 bar.

The engine has to be supplied with the required propellants which are usually Monomethylhydrazine MMH and Dinitrogen tetroxid N₂O₄. The propellant tanks at P1.0 have a capacity of 1.000 L for MMH and 1.000 L for N₂O₄. For both propellants, additional tank capacities of 150 L exist where the temperature is variable.

P1.0 has an infrared camera and a pyrometer available which enable contact-free temperature measurement of the engine.
The command room for P1.0 is located in building M6 next to the P1 test facility complex.

The MCC system consists of a front-end and a back-end computer. The back-end-system is used for the preparation and evaluation of the tests and during tests displays a visualisation of hot run parameters and control of the test facility.

The front-end-computer consists of several individual systems which are connected via a high-velocity-memory. Altogether the computer system has 282 connections for analogue measurements from which 8 can be acquired at frequencies of up to 100 kHz. 504 further channels are available for digital commands.

5.2.3 Utilization and Users

Apart from engines for communication satellites, engines for different research probes have also been tested at P1.0. For example the engine for the Venus Express probe was qualified for its flight by DLR Lampoldshausen.

Additionally, tests of the control thrusters for the ATV-Modules have been performed at P1.0.

The main user of P1.0 is EADS Astrium who regularly uses the facility for the qualification and commissioning of its 400 N Apogee thrusters.

The EADS Astrium development of a next generation 500 N Apogee engine is also currently scheduled to be performed using the P1.0 facility. 200 N thrusters have also been tested at P1.0.

5.3 Test Facilities P2 and P1.2 up to P1.6

In addition to the facilities described in the previous chapters there are other DLR test facilities on the test site which are used by EADS Astrium in the general context of utilisation contracts for EADS Astrium’s own development work. These are namely:

- test facility P2
- small test facilities P1.2 up to P1.6.

Test facility P2, which is the largest of the facilities listed above, was one of the first to be erected on the test site in Lampoldshausen.

P2 has a supply tower to accommodate the sub-systems necessary for tests. It is built into the hill-side so that with an overall height of approximately 28 m, the building protrudes 16 m above road level.

The control room for this test facility is located in building M6 which also has a direct line-off-sight for observation of P2.

The small test facilities P1.2 up to P1.6 are part of the P1 test facility complex. The control rooms are located in building M6 which is arranged as a block house parallel to P1. Here smaller engines for use in satellites are developed.

All the facilities mentioned in this chapter use storable propellants.
5.4 Test Facility P3.2 and Control Building M7

5.4.1 Background

The test facility P3 was originally erected in 1963 in the frame of the ELDO program and was used for the testing of the third stage engine for the Europa launcher. Test facility P3 is still available today under the name P3.1 and can be adapted for future tasks. The original high altitude test facility has been dismantled.

The test facility P3.2 was erected between 1986 and 1988 next to the old P3 test facility building, for the development of the thrust chamber of the Vulcain engine by EADS Astrium.

In 2003 the test facility P3.2 was modified in order to develop the Vinci engine thrust chamber by EADS Astrium.

5.4.2 Characteristics of the Facility

P3.2 was originally built to be capable of providing the thrust chamber of the Vulcain engine with the necessary propellants at the required injection pressures. The propellants are LH2 and LOX and are supplied at up to nearly 200 bar for operation at more than 100 T thrust for up to about 20 seconds.

The test cell of P3.2 is erected behind a solid concrete wall to protect the supply systems. The test cell accommodates the interfaces for supply lines to the combustion chamber together with the thrust stand for the horizontal installation of the combustion chamber. At the outlet a vacuum chamber, an ejector and an exhaust jet guiding system are installed.

The test facility today is able to simulate vacuum conditions for the ignition and start up of the Vinci thrust chamber. The vacuum system is closed during ignition by a cover which is designed to be blown away when the start up pressure of the engine reaches a certain level. Then an ejector keeps the conditions in the vacuum chamber at a level of about 200 mbar for the remainder of the hot fire test.

The vacuum and exhaust system is cooled with water which is supplied from a water tower located directly adjacent to the P3.2 test cell.

The propellant supply system consists of vacuum-insulated run tanks with corresponding feed lines and a pressurisation system. Volumes and pressures amount to 4.5 m³ at 350 bar for the oxygen tank and 12 m³ at 400 bar for the hydrogen tank. The vacuum-insulated feed lines to the thrust chamber in the test cell are also rated for these pressure ranges.

The required flow rate and injection pressure is achieved by pressurising these run tanks with gaseous hydrogen or gaseous nitrogen. The pressure is adjusted by a control computer. The pressurising gas is taken from high-pressure bottles each of which holds 15 m³ and can be charged up to 800 bar from the central gas supply.

The propellants storage tanks are located at the test facility itself and can be directly re-filled by tanker trucks. The available capacities are 30 m³ for LH2 and 30 m³ for LOX. The run tanks are filled from these storage tanks via transfer pipes by means of low-level pressurisation of the storage tanks.

The control room for this test facility is located in building M7 which also allows direct observation of P3.2. The control room houses manual switching panels and regulation valves control units as well as the operator terminals for the control of the test facility.

The MCC system itself is located in another building on site (I2), but it is intended to relocate this system in the future either to building M7 or M8 in order to facilitate operations during test preparation and execution. A study is currently underway to address this issue.
The MCC system is a so-called Albireo system from the French company Eurilogic which was renewed during the modification of P3.2 for Vinci Thrust Chamber Development.

The amplifiers used on the facility are so called Laben-amplifiers which are also located in the I2 building.

5.4.3 Utilization and Users

The main use of P3.2 is currently testing of the Vinci thrust chamber. The main costumer of P3.2 is therefore EADS Astrium.

The modification and subsequent use of the test facility for SCORE-D thrust chamber development is planned. The first steps in this endeavour are currently underway with the evaluation of the necessary modifications to the facility.

The SCORE-D engine is a part of the ESA FLPP program and is designated as a main stage engine.

DLR’s customer for the test facility modification and thrust chamber testing in the frame of this project would also be EADS Astrium.

P3.2 is a very important facility as it is the only European thrust chamber test facility.

5.5 Test Facility P4

5.5.1 Background

The facility P4 was erected for the ELDO program in 1964 and designed with two test cells in one building. P4.1 was intended for testing under sea-level conditions and P4.2 as a high-altitude facility to simulate pressure conditions at high altitude.

The facility had to be modified in 1974 for the Ariane development program and subsequently P4.2 was used to test the Viking engine, the propulsion system for the first and second stage of Ariane 1 to 4. Between 1976 and 1979 test facility P4.1 was used for battleship tests and for testing the complete second stage of the Ariane launcher under sea-level conditions. From 1985 qualification tests were carried out for the Ariane 4 liquid propellant booster rocket (PAL) which resulted in further modification of the P4.1.

The test facility P4.2 was used for altitude tests of the Viking engine until 1981. From 1981 to 1984 more tests under sea-level conditions were carried out for further development of the Viking engine.

The third phase of test facility P4 started with the development of the Ariane 5 launcher. Tests for the upper stage propulsion system using the engine AESTUS had to be carried out in simulated high altitude and also under sea-level conditions.

For this purpose P4.2 was modified in 1991. The high-altitude facility has to maintain a low ambient pressure of just a few millibar throughout the whole test and had to be modified and adjusted to the new test conditions.

A refurbishment of the P4 took place afterwards where a new MCC system, designed and manufactured by the French company Eurilogic, was integrated. Additionally a new building for the steam generator plant was erected.

In 2001 the P4.2 was again modified following an anomaly on the Ariane 5 launcher. A system simulating the configuration of the upper stage was integrated into the vacuum chamber. Since then the tests with the AESTUS engine are performed in this configuration.

In the end of the 1990th it was then decided by ESA to develop a new upper stage for the Ariane 5 including the development of a new cryogenic upper stage engine, the so-called Vinci engine. The system leader of this engine development program is the French company Snecma.

For the development of this engine, the test facility P4.1, which was not in use at the time, was completely modified. The design of this new high altitude simulation facility was done by the DLR Department of Engineering.

Since 2005 this facility has been performing development tests for the Vinci engine under vacuum conditions. At first these tests were performed in the frame of ESA FLPP as a technical demonstrator program. Since 2009 the development tests have been conducted under the ESA ASME program.

5.5.2 Layout of the Test Facility P4

Today the test facility P4 consists of three different facilities: the P4.1, the P4.2 and the steam generator plant P4DE which supplies both P4.1 and P4.2 with the amount of steam necessary to drive the respective high altitude simulation systems.

One building with an overall height of about 30 m contains both test cells, P4.1 and P4.2. The hill side position means that the rear of the building extends
about 20 m below ground level. The front part of the building is designed to accommodate the exhaust components. The rooms in this building are ventilated by means of a pressurised air supply to prevent penetration of any gas or vapour.

The steam generator plant is located in a separate building in the P4 area. The control rooms for test facilities P4.1, P4.2 and the P4 steam generator are all located in building M8 (see chapter 5.7).

Figure 5.17: Test Facility P4 including P4.1, P4.2 and P4 steam generator plant

5.5.3 Test Facility P4.1

Construction of the test facility began in 2000, and the first hot test was run in 2005. Until the middle of 2008, two VINCI engine demonstrators were tested with great success in a total of five campaigns involving 37 individual tests, including re-ignition experiments. The development of an Ariane 5 upper stage equipped with a Vinci engine suitable for commercial use began in 2010. During this campaign a lot of important milestones were reached in the development of the Vinci engine. The first hot fire testing of the complete extendable new nozzle extension, which is made of carbon composite with a ceramic matrix, was successfully performed with the nozzle withstanding temperatures of more than 1,600°C. Additionally, the Vinci engine was re-ignited successfully under vacuum conditions following long and short coast phases.

The development of the Vinci engine will carry on in the next years and the P4.1 is a vital and necessary part in this development.

The Vinci engine is being tested by DLR on behalf of the French engine manufacturer Snecma.

5.5.3.1 Characteristics of the Facility

The P4.1 test facility was built specifically to test the Vinci engine for the new upper stage of Ariane 5. Consuming around 33 kg/s of liquid oxygen and 6 kg/s of liquid hydrogen, the engine generates a thrust of around 180 kN. The height of the engine shown here is 4.2 m overall, and the nozzle has a
diameter of 2.15m at the outlet. When installed in its proper rocket stage, this engine will enable the Ariane 5 launcher to carry 12 instead of its current payload of 10 tons into a geostationary transfer orbit. As the Vinci engine can be reignited, the future upper stage of Ariane 5 will be able to release several payloads in different orbits. Accordingly, the P4.1 test facility was designed for re-ignition under vacuum conditions. At the most extreme operating point, the maximum length of a hot test run on P4.1 is around 700 seconds.

Figure 5.19: Sectional view of the high altitude simulation facility P4.1

High Altitude Simulation System
This layout drawing of the test facility P4.1 helps to explain the basic functions of a vacuum test facility: mounted in the vacuum chamber (1), the engine is supplied with fuel from the tanks (3) by the feed system (2). Expelled vertically downward, the engine exhaust enters the supersonic diffuser. This supersonic core diffuser (4) is of crucial importance for the operation of test facility P4.1. The exhaust (pure water vapor generated by burning liquid hydrogen and liquid oxygen) emerges at several times the speed of sound, and the supersonic diffuser is needed to slow the flow down to subsonic velocities under controlled conditions and convey the gas into the vacuum system without excessive loss of pressure. This system is able to simulate the environmental conditions prevailing in space (vacuum) while the engine is running. The first steam-jet ejector stage (5) removes the exhaust gas and conveys it to the condenser (6). The residual gas is removed by the second ejector stage (7) and reduced to ambient pressure. Together, the ejector stages of P4.1 receive 226 kg/s of steam that is produced by four rocket steam generators. Before each test, the vacuum chamber as well as parts of the altitude simulation system will be 'pre-
evacuated'. Several vacuum pumps are used for this purpose, including a water-ring pump to get the pressure down to 100 mbar. Several sliding-vane rotary pumps accomplish pressures in the low millibar range.

The cooling water for the test facility is stored in three overhead tanks located on the premises. A total of 6,000 m³ of cooling water is kept in store, and there is a refrigeration system for cooling it down to around 7 degrees centigrade.

The engine to be tested is mounted inside the vacuum chamber of the P4.1 and the propellant and gaseous supply lines are fitted appropriately. The vacuum chamber has a weight of 85 tons. Below this chamber the supersonic diffuser is mounted.

This supersonic diffuser decelerates the exhaust gases coming from the Vinci engine from supersonic velocity and recompresses them. The exhaust gases have a velocity of higher than Mach 5 with a stagnation point temperature of higher than 3000 K when leaving the engine. The supersonic diffuser is the biggest component of this kind in Europe.

In the condenser the entering exhaust gases are sprayed with more than 4000 litres of cooling water per second in order to condense the water contingent contained within.

The condenser had to be built on the construction site in Lampoldshausen as it would have been too big for transport on the roads. Around 450 tons of steel were used and the volume of the structure totals around 1500 m³.

Before a test the vacuum chamber and further components of the high altitude simulation system have to be evacuated. For this purpose the following vacuum pumps are available:

- a water ring pump as a booster pump for pressures down to around 100 mbar
- three vacuum pumps for pressures down to a few mbar.

The test facility P4.1 is supplied by cooling water from the three central cooling water towers through two lines.

For a test on P4.1 the complete water reservoir of around 6000 m³ has to be cooled through a water re-cooling system down to around 7 °C.

Another small water reservoir is located on the P4.2 side of the test facility. The reservoir accommodates around 300 m³ of cooling water and is used as water for fire fighting as well as for supplying the steam generators in the P4 steam generator plant.

To supply the test facility P4.1 with cooling water the geodetic water pressure from the water towers is not sufficient. Therefore two water pumps are installed at P4.1 in a separate building. They are used to increase the pressure in order to supply the supersonic diffuser with cooling water and have a power consumption of 1300 kW each.

**Engine Propellant Supply**

The Vinci engine uses liquid hydrogen (LH2) and liquid oxygen (LOX) as propellants. In the run tanks 135 m³ of liquid hydrogen at 20 K and 50 m³ of liquid oxygen at 90 K are present. Two additional small buffer tanks, one for each propellant, are also available to simulate flight start up conditions for the Vinci engine.

During a test the liquid propellants have to be conveyed through vacuum-insulated pipes to the turbo pumps of the engine which is mounted in the vacuum chamber of P4.1. This is done by pressurizing the liquid hydrogen tanks with gaseous hydrogen and the liquid oxygen tanks with gaseous nitrogen.
The filling of the liquid propellant tanks at P4.1 is performed during the test preparation phase, the liquid hydrogen being transferred from the central liquid hydrogen storage area T58 and the liquid oxygen being transferred via a specific vacuum-insulated line from the liquid oxygen propellant tank of the P4 steam generator plant.

**Gaseous Supply System**

The gaseous nitrogen, helium, hydrogen, oxygen and propane are supplied at different pressures up to 320 bar and associated mass flows up to several kilograms per second.

For this task specific gaseous supply systems are installed in the test facility P4.1. The supplied media are mainly for the following functions:

- supply of the engine with helium at nominally 45 bar (range between 30 to 60 bar) as command and venting pressure
- supply of the ignition system of the engine with 200 bar gaseous hydrogen and 200 bar gaseous oxygen
- supply of the ignition system of the engine with 80 bar helium for venting purposes
- supply of the tank pressurization systems
- blow-out of the propellants after a test from the engine itself and all lines which were in contact with propellants during the test
- post-test purging and warming up of all lines which were in contact with propellants during the test
- venting and diluting of leakages if necessary
- safety pressurisation and purging of lines and volumes with nitrogen or helium
- use of helium as sealing gas in the oxygen turbo pump of the engine
- supply of propane burners in order to systematically burn all gaseous hydrogen coming from the bench lines
- supply of the command pressure circuit of the bench which uses gaseous nitrogen in order to switch pneumatically controlled valves.

**MCC – System**

The front-end computers are connected via an optical high-performance network as well as via a high-speed memory (Reflective Memory). The connection to the back-end computers is also performed via optical cabling.

At the test facility P4.1 13 front-end computers perform the following functions:

- LF data acquisition of up to 864 channels with a rate of up to 1000 Hz
- HF data acquisition of up to 88 channels with a rate of up to 100 kHz
- Command system for up to 1.400 digital signals and several diverse command sequences, regulation routines and monitoring
- Control of the backup system.

The MCC system is a real-time system with a time resolution of 1 ms. As all measurement data is available online during a hot fire test, calculations and regulation can be performed throughout the test.

On the test facility P4.1 more than 20 GB of data is acquired and stored during only one test lasting maximum of 700 seconds.

**5.5.3.2 Utilization and Users**

The P4.1 is currently dedicated to the Vinci upper stage engine development ESA A5ME program. System leader of the Vinci engine development is the French company Snecma. The basic maintenance of the P4.1 is conducted under a direct contract from ESA ARTA to DLR.

The Vinci development campaigns are scheduled to continue up to at least 2016 at P4.1.

In order to achieve full qualification of the engine, the facility will undergo further modifications and adaptations such as the possibility to perform tests under sea-level conditions or installation of flight or flight-type hardware which can be qualified on the test facility in addition to the engine itself.

It can be said that the test facility P4.1 is the latest and highest-performance test facility which is available in Europe. It is of absolute necessity in the development of the new cryogenic upper stage engine Vinci. It is unique in its functionality and demands a high level of know-how and experience for operation and maintenance.

**5.5.4 Test Facility P4.2**

Since P4.2 was refitted for engine stage configuration tests in 2001, it has been used mainly for vacuum tests with hot run times varying between 0.8 seconds and 300 seconds, depending on test requirements.
Since 2001, the AESTUS engine has been tested on P4.2 in its flight-stage configuration.

Figure 5.21: AESTUS engine in the vacuum chamber of test facility P4.2

5.5.4.1 Characteristics of the Facility

The P4.2 is equipped for testing rocket engines or complete engine stages with storable propellants.

Five high-pressure bottles in the upper section of the building at the P4.2 each with a capacity of 1 m³ provide nitrogen at 200 bar. The nitrogen is used for pressurising the propellant tanks, blowing out the propellant pipes and flooding the vacuum chamber at the end of the hot run.

In order to handle the dangerous propellants safely a respiratory air supply (1 m³ at 200 bar) is installed. Of course the operating staff wears full protective suits at all time.

Engine Propellant Supply

The propellants used in this test facility are the toxic fuels dinitrogen tetroxide (N2O4) and monomethylhydrazine (MMH). After the combustion stops, the pressurisation gas must be drained from the propellant tanks. All supply lines must be drained of the residual gas before they are opened. The recovered gases contain propellant vapours and are cleaned at the P4.2. N2O4 is scrubbed with a sodium hydrogen solution. MMH vapour is condensed out in a cold trap.

The propellant storages are located in separate rooms on either side of the test facility. The propellants are stored in stainless steel storage tanks each with a capacity of 25 m³ at a pressure of up to 5 bar. Before a test starts, the propellants are pumped into the run tanks in the upper part of the P4.2 test facility above the high-altitude chamber.

The original arrangement for tests with the Viking 4 engine of the second stage of the Ariane 4 launcher is still present. This consists of a double tank, arranged one above the other as in the flight hardware configuration. However, the AESTUS engine uses two propellant tanks each with 1.5 m³ capacity and an operating pressure of up to 40 bar.

In case of problems the propellants are drained back from the run tanks into the storage tanks. As the propellants represent a health risk, all activities at P4.2 involving propellants are subject to strict safety precautions. Specific safety equipment is in use and safety training for the personnel is carried out regularly.

High Altitude Simulation System

The high-altitude chamber of P4.2 measures 4.9 m in height with a floor space of 2.8 m x 2.8 m. In the upper section of the chamber, the engine is connected mechanically to the propellant pipes of the stage simulation tanks and to the thrust measurement device and is connected electrically to the measuring and control lines.

Before a test starts the altitude chamber and parts of the high-altitude facility are evacuated by means of several vacuum pumps: a water-ring pump as a preliminary pump down to 100 mbar and two vacuum pump units for pressures in the low millibar range.

The exhaust jet from the engine flows vertically down into the supersonic diffuser which also contains an auxiliary nozzle powered by the steam generator system with 12 kg/s of steam. Following the supersonic diffuser an initial exhaust cooler is located horizontally at the bottom base of the building shaft. This system can be closed by a hydraulic vacuum valve which has a fast closing function for emergency stop in order to protect the engine. The first ejector stage is connected to this hydraulic valve and is supplied by the steam generator plant with 32 kg/s of steam during a test. A second vertical cooler and a second ejector stage powered again by 32 kg/s of steam complete the whole arrangement of the altitude simulation system of P4.2 (see figure 5.22 below).

Vacuum generation at P4.2 basically follows the same principles as at P4.1, the only difference being that the diffuser is less sophisticated, and there are only two ejector stages fed by only two rocket steam generators.
The test facility P4.2 is supplied with cooling water from the two cooling water towers N33 and N63 via a supply line with a diameter of 1 m. The geodetic water pressure form the water towers is not sufficient to meet all demands, so that there are water pumps to increase the pressure especially to cool the supersonic diffuser. The potentially contaminated cooling water from the P4.2 facility is collected in a specific underground water storage tank below the facility and treated in the N39 decontamination facility (see chapter 5.1.6).

**MCC – System**

The MCC – System of P4.2 is of the same design and functionality as that for P4.1. However, the number of available channels is lower at P4.2.

**5.5.4.2 Utilization and Users**

The test facility P4.2 is currently dedicated to further development and flight acceptance testing of the AESTUS engine. The company EADS Astrium is designing, developing and producing the upper stage engine AESTUS. P4.2 is the only facility to perform hot fire tests of the AESTUS engine.

The test facility P4.2 currently performs not only AESTUS ARTA test campaigns but also the flight acceptance testing of each AESTUS engine before integration into the Ariane 5 upper stage.

The flight acceptance campaigns of the AESTUS engines which will be used for the Ariane 5 upper stages delivering the ATV (Automated Transfer Vehicle) into orbit and subsequently to the ISS currently have the highest priority. These engines are qualified for flight at the test facility P4.2 with a special test profile.

The facility is maintained and kept technically up to date through a direct ESA ARTA contract to DLR. Today P4.2 is the only test facility in Europe which enables the testing of large engines with more than 20 kN thrust using storable propellants both under vacuum and sea level conditions. Therefore the P4.2 is strategically important for European space flight and it is necessary to keep the competency for performing this kind of testing.
5.5.5 Test Facility P4 Steam Generator

Figure 5.23: Test Facility P4 Steam Generator (photo on upper position shows the building while the photo on the lower position shows the steam generator installation)

5.5.5.1 Characteristics of the Facility

The steam that is needed for operating the vacuum system is provided by rocket steam generators which, developed by the DLR engineering department at Lampoldshausen, run on alcohol and liquid oxygen (LOX).

The available tank capacities are
- 38000 L alcohol
- 74000 L liquid oxygen.

Tank capacities are designed for 1000 seconds of operation of the complete steam generator plant.

The steam leaves the generators at a pressure of 22 bar and a temperature of 210 °C. The acceleration to supersonic speed is generated by the vacuum system ejectors. Very low pressures are achieved and the chamber is almost evacuated.

The steam generator plant consists of 5 steam generators:
- two steam generators with a performance of 55 kg/s each
- two steam generators with a performance of 50 kg/s each
- one steam generator with a performance of 16 kg/s.

All five steam generators are in operation for a hot run of the Vinci engine at test facility P4.1. The two steam generators delivering 50 kg/s of steam are used in the operation of P4.2, and bypass nozzles are installed to draw off part of the steam mass flow.

The thermal output of the five steam generators is around 650 MW.

The fuel and the water needed for the steam generation are transported by one set of pumps per steam generator.

Next to the fuel tanks, the steam generator building houses eight high-pressure cylinders, each containing 1m³ of gaseous nitrogen at 320 bar. Among other things, the gas is used to purge fuel lines after the end of each test and to control the pneumatic valves. For these purposes, the gas pressure is reduced via regulators to between 8 bar and 40 bar.

The steam generators are ignited by igniters supplied with gaseous hydrogen and gaseous oxygen.

Figure 5.24: Test on P4.1 with complete steam generator plant operation

The steam generator plant possesses a separate dedicated MCC system and can therefore be operated independently from P4.1 or P4.2. The design of the MCC system itself is similar to the ones on P4.1 and P4.2.
There are complex communication protocols in place which enable the MCC system of the steam generator to communicate with the MCC systems on P4.1 and on P4.2. This is necessary during the hot firing tests in order to harmonize the sequences and operating conditions of the two facilities. In case of problems during engine testing, either with steam generation or on the test facility side, there are redline safety measures in place in the respective MCC system facilitating fast and safe triggering of emergency shutdown procedures.

5.5.6 Utilization and Users

The users of the P4 steam generator are the test facilities P4.1 and P4.2. Parallel operation of the two facilities is possible. The test cadence is determined by the time needed to re-fill the tanks of the steam generator plant and to perform post-test evaluation of hardware and data.

5.6 Test Facility P5

5.6.1 Background

After a longer phase of design and procurement the start of the erection of the test facility P5 and its associated facilities such as the cryogenic tanking and storage areas was in April 1988. Commissioning was finished in July 1990 and the first test of a Vulcain engine was performed in October 1990.

The Vulcain engine is the sole main stage engine of the ARIANE 5 launcher and has meanwhile achieved an outstanding reliability. The engine was developed by the French company Snecma under an ESA program. For erection and the commissioning of P5 the French Space Agency CNES, was acting on behalf of the European Space Agency and was responsible for the contractual framework of these activities.

P5 was modified in 1998 in order to be compatible with the development of the Vulcain 2 engine, the more powerful successor of the Vulcain engine.

The testing activities with this engine started in 1999 with the first test of a Vulcain 2 engine on P5. Up to today the facility is used to test these engines mainly in the frame of the ESA ARTA program.
5.6.2 Characteristics of the Facility

Layout and Exhaust Jet Guiding System

The P5 building itself has an overall height of 65 m. The operation rooms and the propellant tanks are separated and protected from the test chamber by a wall of approximately 2 m thickness.

The test cell accommodates the engine and provides the necessary connections for supply, control and measurement systems. The floor of the test cell is closed by an octagonal slab which is opened during a test to the jet guiding tube which is connected below the engine.

During a test the jet guiding tube and subsequent deflector are necessary for safely deflecting the engine’s exhaust jet up and away into the open air. The system is under considerable thermal load during testing and is cooled with water at a rate of approximately 2500 L/sec.

Cooling water is supplied by the cooling water towers N33 and N63 (see chapter 5.1.6) to the jet guide tube and jet deflector through a pipe with 1 m diameter. One part of the system uses geodetic pressure in order to provide the necessary cooling water flow rate but the section of the deflector subject to the highest thermal load from the exhaust jet of the engine is supplied with cooling water using a booster pump.

During engine start up and shut down phases the exhaust jet is not fully established and can lead to still burning propellants being discharged up into the test cell. To avoid this there is a ring-shaped pipe on the top of the guide tube intake which blows nitrogen at a pressure of 20 bar down into...
the guiding tube through a series of nozzles. The nitrogen flow functions like a jet pump and extracts the burning gas at the exit of the engine safely down into the guiding tube.

The test cell is additionally fitted with a rigid thrust frame in order to accommodate the engine thrust. The thrust frame has a conical shape, approximating that of the Ariane 5 launcher itself, with the engine mounted at the tip of the cone and the upper, open end transferring engine thrust into the test cell structure. The propellant and media supply lines, together with control and measurement cables, pass through the top of the thrust cone down to the engine, in an arrangement which closely resembles that of the actual launcher.

Access to the engine during the preparation phase is made possible via platforms which are pneumatically raised away from the engine during testing.

**Engine Propellant Supply**

The Vulcain 2 uses LH2 and LOX as propellants. The tanks on the bench have a capacity for 600 m³ LH2 at 20 K and 200 m³ LOX at 90 K.

The LOX tank is located in the P5 building at the same height above the engine as in ARIANE 5 launcher itself to mimic the configuration of flight hardware. During the test the liquid propellants in the tanks are pressurized by gaseous hydrogen or gaseous nitrogen and transferred to the engine via vacuum-insulated pipes.

The tanks can be pressurized up to a maximum of 6 bar for hydrogen and 15 bar for oxygen. The propellant tanks at the test bench itself are filled during the preparation phases from the tanks in the propellant depots T23 and T58 (see also chapter 5.1.2) which are connected to P5 via vacuum-insulated pipes.

**Gaseous Supply System**

In addition to the propellant supply, both the engine and the test facility systems themselves must be supplied with other gaseous media at varying pressures and flow rates. Namely nitrogen, hydrogen, helium and propane are supplied at pressures of up to 70 bar and flow rates up to several kilograms per second. These supply systems are used for:

- supply of command pressure to the engine (70 bar GHe)
- tank pressurization
- purging and heating of pipes to remove any remaining propellants
- propane to supply the burners for burning of stray hydrogen
- nitrogen as a drive medium for the pneumatic test facility valves.

At the test facility P5 the following gaseous capacities are available:

- hydrogen 5 x 8 m³ at 220 bar
- nitrogen 5 x 8 m³ at 220 bar,
- helium 2 x 8 m³ at 220 bar.
These tanks are filled from the central gaseous supply system during the preparation phases before the test. A separate system with the capacity of 10 m³ at 200 bar provides the nitrogen required for the exhaust jet guiding tube suction system described previously.

**MCC System**

The MCC system of the test facility P5 together with the command room is located in the building M8 (see chapter 5.7).

The old MCC system was renewed in 2008 to 2009 after more than 20 years of operation.

This current system is therefore the latest and highest-performance MCC system on the Lampoldshausen site. The system was designed and built by an industrial consortium of the German company Werum, the Belgian company Cegelec and the German company SEA.

The system consists of three levels: the frontend, the midlevel and the backend.

The functionality of the frontend, which is used as the test bench interface facilitates:
- Real Time Control
- Data Acquisition
- Real-time treatment
- Majority logics.

The functionality of the system midlevel, which is used as a storage and gateway system includes:
- Data Distribution and Storage (DDS)
- Measurement data, storing and archiving and distribution to clients
- Configuration Management (CM)
- Health Monitoring for Server and Backend
- Periphery management (GWS)
- Frontend Access during configuration
- Safety Aspects: Redundancy on DDS and CM, Dedicated interconnection, Buffering while streaming data (TCP/IP).

The functionality of the backend, which is used as user interface, consists of:
- Control Terminals (inside control room)
- Preparation Terminals
- Running the main Application “OTMP”
- Core Functionality (User Management, Version Management, OTMP)
- Test Configuration (Defining Measuring Points, Creating Sequences, ML, Control loops)
- Test Execution (Data Visualization)
- Data Export and Treatment (Export, Backup, Archive).

There are different types of front ends available:
- Two for Low Frequency Acquisition (max. 1000 Hz, Bandwidth 200 Hz)
- Two for High Frequency Acquisition (max. 100 kHz, Bandwidth 20 kHz)
- Two CS for Command and Control
- One for Real Time Treatment.

Communication inside the MCC system is realized via the following networks:
- a reflective memory network between the frontends for sharing of information
- a process network for streaming data
- a configuration network for system and periphery configuration
- IRIG-B for time synchronization
- One separated network between backend and frontend.

![Figure 5.28: Scheme of P5 MCC system architecture](image-url)
The P5 MCC system is the first fully redundant system where the loss of data is by design virtually impossible. A complex surveillance logic (Watchdog logic) was implemented.

The system was already used for one test campaign with a Vulcain 2 engine on P5 in 2009 and performed successfully. It is fully operational and has greatly improved the performance of the test facility.

Utilization and Users

The development of the Vulcain engine took place from 1990 to 1995. During that time 147 tests were performed with an overall duration of more than 44,000 seconds. The tests varied in length from a few seconds up to 900 sec. The Vulcain engine, with a thrust of 1100 kN and a consumption of 600 L/s LH2 and 200 L/s LOX, was tested for various operating parameters.

The development and qualification program of the Vulcain 2 engine, with a thrust of 1300 kN, has been running since 1998. Since the beginning of the program, 128 tests with an overall duration of more than 56,000 seconds have been performed at P5. The tests have varied in length from a few seconds up to 814 sec.

Today mainly ARTA tests with Vulcain 2 engines are conducted at the test facility P5 and will continue in the coming years.

Furthermore the test facility P5 is equipped for development testing. Therefore, modifications to the existing engine can be tested within the ARTA campaigns.

It is foreseen to modify P5 in the coming years in order to accommodate the SCORE-D engine in the frame of the High Thrust Engine (HTE) development under an ESA FLPP contract. DLR is currently starting the design phase for these modifications.

Additionally the infrastructure of the P5 facility is intended to be used for a new test facility, so-called P5.2, which will be used to test the new cryogenic upper stage for the Ariane 5 launcher in the frame of the ASME program of ESA.

Currently the bench is prepared to perform the next test campaign ARTA in 2011 with a Vulcain 2 engine.

Additionally several refurbishment activities are being conducted in the frame of the ESA ARTA Renewals and Upgrades Program. These refurbishments are important in order to keep the facility up to date, especially considering the wide range of activities which are foreseen in the coming years.

5.7 Control Building M8

The buildings M7 and M8 were erected together with test facilities P3 and P4 during extension of the test facilities for the ELDO program. M8 was then later extended, renovated and modernised as part of the Vulcain project as a measurement and control building for the test facility P5.

Building M8 is located between P3 and P4 with respect to the test facilities and is connected to the facilities P1 up to P5 by an accessible cable tunnel. The building is within the danger zone of the test facilities P5 and P4 and is therefore rated for overpressure conditions and has a secure air-conditioning system.

Building M8 accommodates mainly two independent installations

- The complete MCC system for test facility P5, together with a closed circuit television system for observation of test facility P5, intercom equipment for communication between the staff participating in the various phases of the test and a time distribution system with central timer to monitor the test time. The control room for the test facility P5 is also located in M8 (see fig. 5.30).

- The back-end parts of the MCC systems for the test facilities P4.1, P4.2 and P4 Steam Generator together with the control rooms for these facilities as well as the respective video and intercom systems (see fig. 5.31).
Upper Floor

The control rooms for the P4.1, P4.2 and P4 are integrated on the upper floor of M8. As the operators of the P4 steam generator facility have to work closely together either with the operators of P4.1 or P4.2, this control room is located in the middle. It is connectable to either one of the other control rooms by opening full-length shutters which separate the control rooms.

The back-end part of the MCC system is located directly next to the control room of the P4 steam generator plant.

The MCC system of the test facility P5 together with the signal conditioning units are also located in this part of building M8.

Lower Floor

The lower floor of building M8 houses the control room for test facility P5 together with the closed circuit television system, intercom and time distribution system for this facility.

Next to the control room for P5 is a meeting and visitors room which has a window into the control room to allow visitors to observe testing without disturbing the operators.

M8 further houses several offices, electronic laboratories and a storage room for electronic components, as well as rooms for building services such as cable distributors, an electric distribution system and an air-conditioning system.

5.8 Test Facility P6.1

5.8.1 Background

The test facility P6 was erected in the mid 1960s in order to perform national research programs with respect to high energy propellants.

P6 was finalized in 1966 with two test cells – P6.1 and P6.2.

At the test facility P6.1 tests with combinations of liquid hydrogen and fluorine were performed. At P6.2 combustion driven HF and DF lasers were investigated.

Later, steam generators using hydrogen and oxygen were developed here. Therefore the test facility was equipped with tanks for liquid hydrogen and liquid oxygen as well as independent energy supply systems, a cooling water system as well as a room for test observation for measurement equipment. A nearby building houses offices, a preparation room and a storage room for measurement equipment and tooling.
5.8.2 Characteristics of the Facility

P6.1 was designated as a Green Propellant Test Facility and is capable of use with the following propellants:

- liquid oxygen
- methane / natural gas
- hydrogen.

With a range of interface pressures of up to 90 bar and propellant mass flows of up to 1.25 kilograms per second, the test facility P6.1 is less powerful than the P8. Nevertheless the size of P6.1 classifies it above that of a laboratory. Therefore, only professionally trained teams are allowed to operate this facility.

P6.1 offers favourable conditions for the application of optical diagnostics.

Test Specimen Propellant Supply

The system for liquid oxygen consists of one run tank (106 litres) which can be cooled down using a shell filled with liquid nitrogen. The liquid oxygen is transferred from a storage tank into the run tank before the hot firing test. The tank pressurisation is realized with gaseous nitrogen which is stored in several high pressure bottles.

During a test the mass flow to the test specimen is regulated by a specially developed valve and regulation algorithm.

The conditioning of the feed line before and after testing is done with gaseous nitrogen venting.

The exhaust gases from the fuel system are collected in a catch tank and then burned via a flare stack.

The maximum achievable pressure in the fuel system is 150 bar, the maximum mass flow is currently 250 grams per second for hydrogen and 500 grams per second for methane.

The test specimen can also be supplied with liquid methane through the fuel system. For this purpose the fuel run tank is also enclosed with a shell of liquid nitrogen in order to liquify the fuel. The feed lines are also equipped with jacket cooling systems.

Gaseous Supply System

As mentioned above the supply of the facility with gaseous nitrogen is necessary for pressurisation, purging and venting reasons. This is done with gas bottles and provides pressures of up to 40 bar.

The ignition system uses gaseous oxygen and gaseous hydrogen supplied from gas bottles with up to 60 bar pressure.

MCC System

The MCC System for test facility P6.1 was designed and delivered by the German company Werum and uses the software LabView.

128 LF measurement channels and 16 HF measurement channels are available.

5.8.3 Utilization and Users

The test facility P6.1 went into operation in 2009 and is foreseen to perform test campaigns in 2010 for EADS Astrium and DLR research projects.

P6.1 is open for a wide range of users and complements the portfolio of testing possibilities at DLR Lampoldshausen.
5.9 Test Facility P8 and Control Building D68

Figure 5.33: Test Facility P8

5.9.1 Background

Initial plans were made by the DLR back in 1990 for a research test facility for high-pressure combustion with hydrogen and oxygen. In December 1992, work started on the construction planning for a European research and test facility on the basis of a Memorandum of Understanding between DLR, the French Space Agency CNES and the industrial companies Snecma in France and EADS Astrium in Germany. This agreement was the first of its kind to succeed in arranging joint financing of a test facility for use by different partners. The facility was planned, constructed and commissioned and is today operated by DLR on behalf of the various users. The first test was conducted in 1995 and since then more than 2000 tests have been performed at this facility.

Since the first test several additions and modifications have been made to the facility in order to increase potential applications. These include:

- the addition of a gaseous methane propellant supply system
- the addition of a noise reducing guide tube system.

5.9.2 Characteristics of the Facility

The essential features of the test facility P8 can be summarised as follows:

- high availability rate (100 test days per year) made possible through the construction of two identical test cells P8.1 and P8.2.
- high-pressure propellant supply systems for oxygen and hydrogen providing pressures at the interface to the test specimen of up to 360 bar at mass flows of up to 8 kg/s for LOX and 3 kg/s for LH2.
- High-pressure cooling water supply system for a maximum flow rate of 50 kg/s at 200 bar system pressure
- Test times of up to 15 seconds at maximum mass flow
- Possibility for cooling the hydrogen to the temperature of liquid nitrogen
- High-precision mass-flow regulation valves.

There are two rooms adjoining each test cell where optical measuring instruments can be installed. There are also connections available for data acquisition and remote control of these instruments.

Oxygen and cooling water are conveyed to the test specimen through pressurization provided by the high-pressure nitrogen system. Gaseous hydrogen can be supplied to the test specimen in a “warm” or “cold” state. The regulated mixture of ambient temperature (warm) gas and gas cooled using a liquid nitrogen heat exchanger (cold) makes it possible to adjust the temperature in a range from 100 to 150 K with pressure levels up to 260 bar at the interface.

Test facility P8 is capable of operating under a wide range of conditions with regard to mass-flow and supply pressure at the interface to the model combustion chambers. High pressure mass flow regulating valves, equipped with roller spindles and actuators, facilitate adjustment of mass flows with a precision of 1 % and also allow for quick changes in mass flows. In this way several different operational points can be achieved during a single test so that the overall number of tests can be optimized.

Control Building P8

The control room for P8 is located in the building D68. D68 houses the central measurement and control installations for test facility operation, as well as various laboratories and office rooms. The observation and control room does not have direct visual contact with the test facility.

All functions at P8 are delegated to decentralized computers. The individual components are located...
in control building D68 and test facility P8. VME front-end computers with real-time operating system and process periphery equipment are located at the test facility. A back-end computer under operating system HP-UX is located in building D68.

A fast databus connection facilitates communication between the measuring and control components.

5.9.3 Utilization and Users

The facility is still operated under the aforementioned Memorandum of Understanding which has successfully been in use for more than 15 years. The bench is operated by the department of test facilities. Planning for the occupation of the facility is proposed by a scientific and a steering committee. The members of the scientific committee as well as the members of the steering committee are representatives from the different entities involved in the MoU for P8. These are:

- representatives from the French Space Agency CNES
- representatives from the French industrial company Snecma
- representatives from the German branch of the industrial company EADS Astrium
- representatives from DLR.

The steering committee is headed by the DLR Director of the Institute of Space Propulsion Lampoldshausen.

The need for renewals and upgrades is also addressed and decided upon in these two committees and the necessary financing is shared according to the MoU.

The test results obtained at the test facility P8 are often used for the verification of computer based modelling tools. The main research topics benefiting in this respect are the evaluation of heat transfer parameters using caloric combustion chambers and the testing of thermal protection layers.

Basic experiments for the development of new injection elements are performed, as well as testing of improvements on already qualified systems. Additionally the testing of equipment for test facilities themselves has been realized at P8. For example the supersonic diffuser which is currently operating at test facility P4.1 was tested as a subscale model at P8.

Plans for the near future include installation of a liquid methane propellant supply system and an altitude simulation system for the test facility. These assets will greatly increase the functionality of this unique test facility.

5.10 Test Facility P6.2

The test facility P6.2 has been developed for studies in the field of gas dynamics using cold gas conditions. A specialized capability of P6.2 is the simulation of transient environmental pressure conditions similar to those experienced during the flight of a launcher. Objectives are the improvement of altitude simulation techniques and basic research in nozzles.

P6.2 has an altitude simulator with variable pressure conditions. The pressure can be regulated from $p = 1$ bar for sea level conditions down to $p < 10$ mbar for high altitude conditions. One of the drivers is the investigation of flow separation and transition phenomena in nozzles of the dual bell or plug type. Additionally there is the possibility to have supersonic surrounding flow conditions.

P6.2 consists of a vacuum chamber combined with exchangeable super- or sub-sonic diffusers and an optional ejector system.

![Principle of P6.2 Test Facility](image)

Figure 5.34: Principle P6.2

The principle allows the regulation of the pressure inside the vacuum chamber depending on the behavior of the diffuser, ejector and the bleed gas injection.
### Conditions

<table>
<thead>
<tr>
<th>Description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply system</td>
<td>N₂ cold gas, m = 2.8 kg/s (optional 4.2 kg/s), pressure regulated from P = 10 up to 40 bar (optional 55 bar)</td>
</tr>
<tr>
<td>Test time</td>
<td>&gt; 60 s with full flow</td>
</tr>
<tr>
<td>Altitude simulation</td>
<td>Vacuum chamber &lt; 10 mbar – 1 bar, adjustable for the research of transition phenomena</td>
</tr>
<tr>
<td>MCC</td>
<td>64 LF channels up to 1 kHz, 16 HF channels up to 100 kHz, 32 digital I/O, 4 GB capacity</td>
</tr>
</tbody>
</table>

Figure 5.35: P6.2 conditions

Figure 5.36: Test position P6.2

Different visualization techniques have been used during nozzle research, like Pressure Sensitive Paint (PSP), Backflow Frosting (BFF), Infrared Thermography (IRT) and Schlieren Optic.

**5.11 M3 Laboratory**

**5.11.1 M3.1**

M3.1 is a small scale test facility used for the basic phenomenological analysis of cryogenic injection and combustion. The scale of the bench allows a high test cadence enabling extensive parameters studies.

The propellant combinations used to date include O₂/H₂, O₂/CH₄, O₂/C₃H₈, and O₂/C₃H₆. Injected oxygen can be either liquid (cryogenic at ca. 85-90 K) or gaseous (at ambient temperature). The cryogenic conditions are obtained through a liquid nitrogen bath at 77 K, where O₂ can be liquefied inside a run tank, and then pressurised to the desired pressure with helium. Helium is chosen because of its low miscibility with liquid oxygen in the temperature and pressure ranges in which the run tank is operated.

The feed lines are designed for pressures up to 40 bar. The pressures are set prior to the test through automatic pneumatic dome pressure regulators. This enables a very precise programming of the tank pressures through the measurement and control system, with a typical error of p < 0.1 bar. Run valves are designed for extremely fast opening times (t_open < 10 ms), in order to ensure short transients prior to ignition in the combustion chamber. The mass flows are determined through a Coriolis flow meter for the liquid oxygen line, and through calibrated sonic nozzles for gaseous propellants. By choosing the correct sonic nozzle, the mass flows can be calculated through pressure and temperature measurements upstream of the sonic nozzle. Moreover, sonic nozzles provide an effective separation between feed lines and injector head, thus minimizing low frequency instabilities that could arise during combustion.

**5.11.2 M3.2**

This test bench (see Figure 5.38) allows heat transfer measurements in cooling channels with cryogenic fluids (LN₂, H₂@80K) as well as fluids at ambient temperature (CH₄, He). Maximum pressures are up to 4 MPa and maximum mass flows up to 40 g/s. The bench is equipped with a high accuracy mass flow meter. A precisely controlled electrical power supply system enables the realization of heat fluxes of up to 20MW/m².
the same order of magnitude as in real rocket combustors.

Figure 5.38: Test bench M3.2 for the investigation of electrically heated cooling channels

5.11.3 M3.3

The test bench M3.3 (see Figure 5.39) is designed for investigating high frequency (HF) combustion-instabilities in laboratory scale rocket combustion chambers. Several propellant combinations can be tested under cryogenic (> 77K) or ambient conditions such as liquid oxygen (LOX) and gaseous hydrogen (H2), LOX and methane (CH4) as well as LOX and ethanol (C2H5OH). Furthermore the supply system provides other fluids such as helium (He) and nitrogen (N2) for valve control, pressurizing, purging and cooling the system. LOX is produced by condensing gaseous oxygen in a tank which is located in a liquid nitrogen bath (see frost coated container in Figure 5.39). The combustion chamber is designed for a total mass flow of 10 g/s and combustion chamber pressures up to 1 MPa are possible. The test length is limited to 10 s and tank pressures up to 40 bars can be achieved. The measurement control and command system (MCC) is able to control the test automatically and monitor safety parameters (red lines). Low frequency (LF) and HF data acquisition with acquisition rates up to 100 kHz are possible.

Figure 5.39: Test bench M3.3 for the investigation of high-frequency combustion instabilities

5.11.4 M3.5

The planned M3.5 facility will aim at enhancing the knowledge of phenomena relevant to a cryogenic upper stage in support of the development of the VINCI upper stage. The transient processes in fluid lines prior to and during ignition are one of the main topics of interests.

In order to fully understand ignition processes, it is necessary to understand the engine flow transients, from the time of opening of the main valves to steady state operation of the engine. Due to the difficulty in studying these effects in a real engine (partially due to the complexity of interacting phenomena and partially due to the restrictions in sensor integration and location), the designer has to rely on the quality of their numerical tools. Test data is needed to improve or validate these tools.

M3.5 will provide a facility for experiments of transient two-phase flow and pressure hammer. Emphasis will be placed on the fluids to be investigated. In addition to testing with water, DLR experience in cryogenic engineering will be exploited and enhanced with the use of liquid nitrogen and liquid oxygen. The use of cryogenic fluids will create a unique data base with engine propellants at conditions that are similar to those found in cryogenic upper stages.

M3.5 is currently under construction. Operation with water is planned by end of March 2011. The modular nature of the test bench will allow for subsequent set-up changes to be made. The upgrade for testing of cryogenic fluids is scheduled for mid 2012.

In its current configuration the M3.5 supply system (Figure 5.40) is capable of a maximum flow rate of 1.88 kg/s of water at a pressure of 50 bar. The test section is designed to withstand a pressure of 128 bar.
5.11.5 Cryogenic Laboratory

Hydrogen is stored in the tanks of a cryogenic rocket stage at a temperature of about 24 K. Experimental techniques require therefore qualified temperature sensors at these low temperature levels where the sensitivity of most sensors is drastically reduced and shows nonlinear behaviour. The cryogenic laboratory at the Institute of Space Propulsion (see Figure 5.41.) enables the calibration of low temperature sensors for applications in basic research as well as for applications in the cryogenic test facilities P3, P4, P5 and P8 at the Lampoldshausen site. The liquid Helium infrastructure in the cryo-lab allows calibration at temperatures as low as 4.2 K. The Institute’s calibration capability allows a significant increase of temperature measurement accuracy as compared to when standard calibration curves are used (see Figure 5.42.).

5.12 Thermo-Mechanical Fatigue (TMF) Test Facility M51

A detailed motivation, an exemplary test specimen (TMF-panel) and some specimen test results have been presented previously in section 1. Therefore, the following subsections will deal with the test facility and measurement equipment only.

The Heating Device of the TMF Test Facility

The key component of the TMF test bench is a heating device for the tested wall component. The heating device of the TMF test bench at DLR Lampoldshausen was designed and built by DILAS Diodenlaser GmbH. The key technical parameters of this diode laser are given in Figure 5.43.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelength</td>
<td>940 nm</td>
</tr>
<tr>
<td>optical output power</td>
<td>11 kW</td>
</tr>
<tr>
<td>distance from the optics module to the focal plane</td>
<td>415 mm</td>
</tr>
<tr>
<td>plateau cross section of the beam at the focal plane</td>
<td>19 mm x 51 mm</td>
</tr>
<tr>
<td>homogeneity</td>
<td>better than ±5%</td>
</tr>
<tr>
<td>operational mode</td>
<td>cw</td>
</tr>
</tbody>
</table>

The core part of this laser is the laser head which is shown on the lower left side of Figure 5.44.
A cryogenic coolant proportion, stored in liquid phase in a tank as shown in Figure 5.45 right is mixed with a gaseous ambient temperature proportion of the coolant. The mass flow rate as well as the pressure of the fluid can be controlled by means of computer controlled valves. As the coolant is stored under a relatively low pressure in the liquid tank, the use of a coolant pump as shown in Figure 5.46 is also necessary.

The Measurement Devices
For the determination of the heat flux into the TMF panel, the following values have to be measured:
- the laser power in the focal plane.
- the absorption of the laser loaded surface at the laser wavelength.

For these purposes, the devices as described in the following 2 subsections are used.

Laser Power Meter
A special version of the PRIMES Power Monitor with an aperture of 250 mm x 50 mm as shown in Figure 5.47 left is used for the measurement of the laser power.

The Fluid System
As the TMF panel is realistically heated, it also has to be cooled in a way similar to the original structure being simulated. The fluid system of the TMF test bench provides the cooling fluid for this purpose. The temperature of the coolant can be fully controlled by means of a mixer as shown in Figure 5.45. left.

The TMF Panel Housing
Without a panel housing, the following undesired effects could occur:
- Water vapor condensation effects on the laser loaded side of the TMF panel wall material during the pre- and post cooling processes due to the cryogenic temperature (160 K) of the coolant (Nitrogen). These condensation effects could obstruct deformation measurement systems.
- Endangering TMF test bench personnel due to laser light, reflected by the TMF panel.
In order to avoid the above mentioned effects, a TMF panel housing as shown in Figure 5.44. right was designed.

The Fluid System
As the TMF panel is realistically heated, it also has to be cooled in a way similar to the original structure being simulated. The fluid system of the TMF test bench provides the cooling fluid for this purpose. The temperature of the coolant can be fully controlled by means of a mixer as shown in Figure 5.45. left.
For laser power values between 1 kW and 12 kW, the measurement error of the system is less than ±2% of the measured value.

5.13 Test Bench Complex M11

The test facility M11 at the DLR Institute of Space Propulsion enables investigations of flow, mixing and combustion processes in model combustors relevant for rocket as well as air breathing ramjet and scramjet engines. Four test positions M11.1 to M11.4 are available in two separate test cells. Three of the test positions are equipped with vitiated air heaters, which make use of hydrogen/oxygen burners. Total temperatures up to 1500 K of the vitiated air flows can be realized. The flexible design of the test positions enables fast exchange of test specimens and components.

The test facility provides two separate diagnostic rooms for sensitive (laser-based) diagnostic equipment. The test bench team and the scientists using this facility have experience with a broad variety of intrusive and nonintrusive diagnostic techniques. For some of these techniques detailed adaptation and development work has been conducted. In addition material investigations in combustion chambers and nozzles can also be conducted. The large capacity storage vessels for air, H₂, O₂, and N₂, the remotely controlled execution of the test sequences and the modular design of test specimens make high test frequencies possible.

Available diagnostic techniques and capabilities include:

- Thrust balances at two test positions with air heaters
- More than 200 measurement channels for pressure and temperature in a wide range of sampling frequencies
- Conventional non-intrusive diagnostic techniques, e.g.: Color and BW Schlieren, high speed Schlieren, shadowgraphy, flame spectroscopy, 2D spontaneous OH-emission monitoring, pyrometry
- Laser-based diagnostic techniques partly in collaboration with other departments, e.g.: PIV, CARS, Mie scattering techniques with seeded flows for e.g. mixing processes, Malvern particle sizing
- Intrusive diagnostic techniques, e.g.: water-cooled pneumatic single probes and probe rakes, water-cooled sampling probes for determination of stable species like H₂, O₂, N₂, water, CO₂, etc.

The chemical laboratory servicing the M11 facility is located in the M3 building. A large number of diagnostic techniques and also propellant production capabilities are available for both internal research and external customers. Diagnostic techniques and capabilities include for example:

- wet chemistry analysis
- gas chromatography
- rotational and capillary rheometers
- water and propellant analytic equipment
- kneading machine for solid fuel production
- dissolver stirrer apparatus for gel production
- equipment for the determination of material properties (e.g. density, surface tension, etc.)
- FT-IR and UV-VIS spectrometers, centrifuges, etc.
- laboratory rooms with equipment for material testing in highly toxic or aggressive (propellant) environments like hydrazine or nitrous oxides.

In the G49 building, which is part of the M11 test complex, a separate facility has been developed to enable the production of various gel propellants under remote control, where a higher security level for the involved personnel is necessary.

A test field M11.5 is currently under construction, where student working groups, supervised by the engineers of the department, will conduct experiments with small rocket motors. This test field will serve as support for the STERN program of the DLR space agency. More information is given in the chapter “Campus”.
Figure 5.48: Image of test bench complex M11

Figure 5.49: Image of a test run of a gel model rocket combustor at M11.1 test position
6. DLR_Campus Lampoldshausen

6.1 Scientific and Technical Education

The need for an optimum education is obvious for a research organisation like the DLR in Lampoldshausen. Furthermore the need for young academics in the relevant technical areas of space propulsion is evident. In particular Lampoldshausen needs educated scientists and technical staff, due to the complex research areas and the required performance of the DLR test benches. However, it has been observed over the past decade that the interest of young people in sciences and especially physics, math, chemistry and engineering is decreasing. In combination with the demoscopic change in Germany, it will be difficult to fulfil the need for well trained and educated newcomers in the coming years. Additional to these matters of facts, the current education structure in Germany apparently fails to fulfil the necessary requirements and thus the Federal Republic of Germany (BRD) will face a decline in the scientific and technological knowledge of its population [OECD 2010].

In light of these problems, the DLR Institute of Space Propulsion has implemented a DLR wide initiative - the DLR_Campus – to react and respond. One main aim of the initiative is to advance young peoples interest in science and to give them an initial impulse to study one of the DLR related topics at university. Another aim is the optimization of scientific or technical education as well as the promotion of careers of young people in the DLR. Finally, the DLR_Campus will promote the idea of lifelong learning and thus the continuing education of its employees at the DLR Lampoldshausen. To reach these goals, the DLR_Campus has a structure to afford tailor-made activities for its target groups.

6.2 The DLR_School_Lab

The DLR_School_Lab is one of the columns of the DLR_Campus. Founded in 2005 it provides several activities for intermediate and college pupils with opportunities for them to discover their experimenting skills or their fondness for science or engineering in practical courses and “hands-on” experiments.

Thus the main part of the DLR_School_Lab consists of laboratory days where complete school classes could perform practical and realistic experiments in a lab, which was built especially for the students. The lab offers up to 13 experimental stations on which the students become familiar with the fundamental methodology of science: observing, measuring, modelling and simulation as well as the interconnections between these, through practical hands-on activities.

In this way, pupils obtain a concrete idea of the daily work of research physicists, chemists and engineers as well as of the true nature of scientific research and investigation. Based on current DLR research highlights, the DLR_School_Lab experiments represent a cross-section through DLR’s scientific and technological topics in the fields of space propulsion, aeronautics and energy. All experiments have a modular structure, where the level of difficulty and the duration can be modified. They are tackled independently by small teams (max. five students), with the expert support of DLR scientists.

The DLR_School_Lab extended its experimental offers for students in 2009. In detail, the DLR_School_Lab in Lampoldshausen, has developed a so called Mittelstufen-Parcours (middle-school course) with new experiments especially planned for younger students in the ages between 12-15 years.

Beyond the program in the students’ laboratory, the DLR_School_Lab offers several internships like BOR (Berufsoorientierung an Gymnasien) or BORS (Berufsoorientierung an Realschulen)- activities for...
orientation on a career path. Teachers-workshops are also part of the DLR_School_Lab as well as special events like Girls’Day, or events in the framework of public understanding of science. The DLR_School_Lab has also supported miscellaneous student research activities like “Jugend forscht”-projects or so called “Facharbeiten”. There are also special offers for highly gifted and motivated students like research academies or weekend workshops and the DLR_Talent_School.

Objectives of the DLR_School_Lab

By means of the DLR_School_Lab, the DLR wants to promote the interest of young people in sciences and aerospace engineering. The aim is to encourage them to study sciences or start an education in technical jobs. Another objective is to inform the public about DLR’s research programs.

Target Group DLR_School_Lab

The target groups of the DLR_School_Lab are middle school students, high school students, teachers and interested public. Special target groups are students studying Teaching Methods of Natural Sciences, young women and girls, highly gifted and interested young people.

The Concept of the DLR_School_Lab

How did the DLR_School_Lab arouse interest in scientific topics in young people?

The main concept of the DLR_School_Lab is based on three factors; fascination, authenticity and hands-on experiments.

Fascination

Europe’s most powerful rocket, a big airplane carrying a 17 ton heavy IR-telescope or a water droplet that seems to stand still in front of your nose - all these are topics which fascinate young people. The DLR_School_Lab uses this fascination to show the students that science and engineering isn’t boring and thus gives them the motivation to study these topics.

Authenticity

The laboratory is located in the middle of the DLR test site. Thus the students can work in the inspiring and authentic atmosphere of the DLR test site just like a real scientist. They work on “subscaled” experiments with real scientific equipment that one usually couldn’t find in schools.

The DLR_School_Lab offers experiments close to current research in the authentic environment of the Institute’s test site.

Hands-on experiments

The most important part of the concept is the experiments: The students accomplish the experiments by themselves. They perform their “research” together with real scientific or technical staff of the DLR in small groups (4-5 students) and thus get hands-on experience with science and technology and achieve an authentic impression about scientific work.

Experiments

The variety of the subjects and methods offered at the DLR_School_Lab matches the scope of the individual branches of the Institute of Space Propulsion’s main research activities. The DLR_School_Lab in Lampoldshausen now owns up to 13 experiments. Selected research topics close to the current research areas of the DLR test site Stuttgart are also represented in the Lab:

- Vacuum technology – High altitude simulation
- Combustion and Combustion instability
- Optical Measurements
- Rocket flight

Figure 6.2: Impression of the main concept of the DLR_School_Lab
- GPS and Effects of Special and General Relativity
- Aerodynamics of launchers
- LA$\Sigma$ER
- Microgravity
- Fuel Cell
- Solar Cell and Solar thermal power plants
- Light weight materials
- SOFIA
- Momentum conservation and Staging principle.

Member of the MiNe-MINT e.V.
Associate of the Schüler-Ingenieurs-Akademie (SIA) Strömung, together with University Stuttgart, Fa. Behr, Staatliche Akademie für Lehrerbildung, Phillip-Matthäus-Hahn-Highschool
Associate of the experimenta Heilbronn
Associate of the Juniorakademie Heilbronn

School-Cooperations:

Special Events
The DLR_School_Lab offers special events tailor-made for individual target groups like teachers, girls and young women or highly gifted students and the interested public. These events include lectures, seminars and summer or autumn academies during the school holidays. Some of them are given in English, French or Italian language. Since 2004 the DLR_School_Lab has initialized or taken part in more than 90 special events and exhibits. The collection can be found in the section 7. (CDROM).

Grants
In 2009 the DLR_School_Lab Lampoldshausen received a 3000 Euro award for the three year duration project “Hauptschulraketen”, which was initialized to promote talented students of the Johannes Häussler-Werkrealschule Neckarsulm.

Statistics and Evaluation
Since opening, the DLR_School_Lab in Lampoldshausen has been visited by more than 10,000 students and nearly 1000 teachers. The main catchment area lies in a radius of about 150 km around Lampoldshausen (Fig. 6.4). That means nearly 90 % of the visitors are from Baden-Württemberg. But the DLR_School_Lab also has visitors from other federal states of Germany as well as an international audience e.g. from Italy, France, Austria, Spain, Belgium or Singapore.
Another result of the scientific evaluation is that the pupils feel that they have learned more during one day at DLR_School_Lab than during a day at school. It is also shown that a single visit significantly augments the interest in sciences. This interest has not declined six weeks after the visit [Paw 2009].

Due to these results it is shown, that the DLR_School_Lab can increase students’ interest in space sciences and, of course, enhance the interest in sciences in general – a fundamental necessity to study in science and engineering.

6.3 The DLR_Academic_Lab

The DLR_Academic_Lab constitutes the second column of the DLR_Campus.

Its main features are summer schools, student workshops, extended laboratory programs for students at university level, a rocket-motor test stand, lectures held by internationally known and respected space propulsion specialists and a graduate program for PhD students. The DLR_Academic_Lab will start in summer 2011.
Objectives of the DLR_Academic_Lab

Through the programs of the DLR_Academic_Lab, the Institute of Space Propulsion wants to promote the interest of university students in space propulsion, inform them about the main DLR research activities on the test site, deepen the relationship between universities and the Institute of Space Propulsion and promote the DLR as an attractive workplace.

Target Group DLR_Academic_Lab

The target group of the DLR_Academic_Lab is students at the university level, especially from the scientific faculties and research institutions, doing their Bachelor, Masters or PhD degree, as well as young engineers of the aerospace industry.

Summerschools

In 2007 the DLR in Lampoldshausen launched its first summer school. It was organized by the Institute of Space Propulsion in partnership with the University of Heilbronn. The main focus was on the topic “Space Propulsion”. The summer school has offered courses for students doing their Bachelor, Masters or PhD degree. The month-long course was composed of lectures on different disciplines related to space propulsion ranging from space transportation and launcher systems engineering to project management and costing, history of the Ariane program, communication and media relations. Practical hands-on workshops were also parts of the summer school. The small group workshops were planned in a way that the participants had to use their lecture based knowledge and teamwork strategies for practical laboratory exercises and engineering projects.

Based on this scheme the Institute is establishing an annual summer school on space propulsion and other current topics in the framework of European launcher technologies. The summer school will be open to German and international students of all ESA countries. The summer school will start in summer 2011.

Laboratory

DLR_Academic_Lab will offer several experiments to extend and broaden the subjects of lectures on space propulsion held at the University of Stuttgart or the DLR summer schools. Main experimental topics will be:

- Chemical rocket motors
- Test bench handling
- Nozzle flow
- Measurement techniques
- CFD-Simulations
- CAD Design
- Hydrodynamic Instabilities
- Combustion and Acoustics

Rocket Motor Test Bench for Students

STERN (Studentische Experimental-Raketen) is a program for students, launched in 2010 by DLR.

The program is open for student groups of German universities that offer courses in aerospace engineering.

With support of the DLR, the students develop, build and launch their own rockets. Just as in a real space project several milestones and design reviews have to be achieved by the students. Essential parts of the program are hot firing tests of the manufactured engines and the final flight acceptance tests of the complete rocket motors.

For this purpose the DLR Lampoldshausen is developing a multifunctional test field for the student rocket motors, located at M11 test bench complex.

After passed flight acceptance tests the rockets shall be launched for example from military grounds in Germany in support of the MORABA (Mobile Raketen Basis). For rockets with a target altitude of more than 5 kilometers, the launch will take place at the Espace Space Center in Kiruna.

The requirements for the rocket to be launched are the following. The maximum velocity shall exceed Mach 1, telemetry data should be recorded and transmitted to the ground, a payload should be onboard and the rocket has to be recovered by a parachute system. A possible future goal is to overmatch the European altitude record of 12.55 kilometers for an amateur rocket.

The test field at M11 test bench complex is designed to have room for two 6 m containers. The students can build their test stand at their university in such a mobile container. When their setup is complete and checked by safety tests from DLR, they can place their container on the test field at M11 and conduct their experiments under supervision of DLR. These mobile containers can be
equipped with different test stands for the several used propellants, to allow work on handling, feeding, ignition and combustion especially of hybrid propellants, but also liquid bi-propellants or possibly solid fuels.

The test field will enable the students to conduct basic experiments on the pre flight design engines and later on, to optimize their flight motor and confirm the motor’s flight readiness. The experiments of the students will be supervised by the responsible experts of the department. As basic requirement for the students, and in addition of their test campaigns, seminars about the basics of space propulsion, rocket motor design, safety and risk analysis, operational safety management for test activities, handling of a test bench, measurement techniques, data collection and data analysis will be conducted by engineers and scientists of the DLR.

Workshops

Also part of the DLR_Academic_Lab are annual workshops for students of one week duration. The participants must have completed at least 3 years of academic studies in the field of engineering or science as minimal requirement for participation. The first workshop was conducted in 2008 under the title «Jugend denkt Zukunft».

Within five days the participants learn about factors influencing rocket design and the technologies needed for future launcher development. Hands-on activities let students explore the science and technology required in these topics. Short talks related to specific research problems, given by DLR-scientists, show the participants some of the difficulties encountered in daily practical work on space propulsion.

Graduate Program

The DLR_Graduate_Program was established in 2009. It is a qualification program open for all DLR PhD students. The program develops essential skills of the participants like methodical competences as well as management or social competences. Presentation methods, how to write a scientific proposal or paper, basics of team leading and science communication are main parts of the program.

6.4 Exhibition

An exhibition displaying numerous items from Europe’s 50-year history of space flight forms the historical backbone of the DLR_Campus in Lampoldshausen. The exhibition illustrates the history of the DLR site and provides visitors with an insight in its scientific activities. It also offers background information on the principles of space propulsion and the first experiments with rocket combustion chambers. The exhibition presents decades of development and research work on high-altitude simulation and documents the outstanding competence of the DLR Lampoldshausen test site. It gives students as well as researchers and the interested public a unique insight into the subjects, methods and technologies of space propulsion.

Citations:

[Paw. 2009]: Schülerlabore als interessenfördernde außerschulische Lernumgebung für Schülerinnen und Schüler aus der Mittel- und Oberstufe. Dissertation Christoph Pawek, IPN, Universität Kiel 2009

[OECD 2010]: OECD: Education at a glance 2010
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>A5</td>
<td>Ariane 5</td>
</tr>
<tr>
<td>A5 ME</td>
<td>Ariane 5 Midlife Evolution</td>
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<tr>
<td>AAS</td>
<td>Advanced Altitude Simulation</td>
</tr>
<tr>
<td>ADN</td>
<td>Ammonium Dinitramide</td>
</tr>
<tr>
<td>AESTUS</td>
<td>Engine of Ariane’s EPS Upper Stage</td>
</tr>
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<td>ALD</td>
<td>Air Liquide Germany</td>
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<tr>
<td>API</td>
<td>Advanced Porous Injector</td>
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<tr>
<td>API</td>
<td>Abstracts Front-End</td>
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<tr>
<td>ARTA</td>
<td>Ariane-5 Research and Technology Accompaniment</td>
</tr>
<tr>
<td>ATAC</td>
<td>Aérodynamiques des tuyères et Arrière-Corps</td>
</tr>
<tr>
<td>ATV</td>
<td>Automated Transfer Vehicle</td>
</tr>
<tr>
<td>BFF</td>
<td>Back Flow Frosting</td>
</tr>
<tr>
<td>BK</td>
<td>DLR - Institute of Structures and Design</td>
</tr>
<tr>
<td>BS OHSAS</td>
<td>British Standard Occupational Health and Safety Assessment System</td>
</tr>
<tr>
<td>C/C-SiC</td>
<td>Carbon/Carbon Silicon Carbide (Ceramic Composite)</td>
</tr>
<tr>
<td>C3H6</td>
<td>Cyclopropane (Trimethylene)</td>
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<tr>
<td>C3H8</td>
<td>Propane</td>
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<tr>
<td>CALO</td>
<td>Calorimeter Nozzle Test Campaign</td>
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<tr>
<td>CARS</td>
<td>Coherent Anti-Stokes Raman Scattering</td>
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<tr>
<td>CCN</td>
<td>Contract Change Notice</td>
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<tr>
<td>CERFACS</td>
<td>Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CFX</td>
<td>Commercial CFD Tool (ANSYS Corp.)</td>
</tr>
<tr>
<td>CG</td>
<td>Conjugate Gradient</td>
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<tr>
<td>CH4</td>
<td>Methane</td>
</tr>
<tr>
<td>CM</td>
<td>Configuration Management</td>
</tr>
<tr>
<td>CNES</td>
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<td>Centre National de la Recherche Scientifique</td>
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<td>CRC</td>
<td>Common Research Chamber</td>
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<td>CRE</td>
<td>Compte-rendu d’essai</td>
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<tr>
<td>DDS</td>
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<td>Deutsche Forschungsgemeinschaft (German Research Foundation)</td>
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<td>DIN</td>
<td>Düse Inconel (Inconel Nozzle)</td>
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<tr>
<td>DMA</td>
<td>Direct Memory Access</td>
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<td>EADS</td>
<td>European Aeronautic Defence and Space Company</td>
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<tr>
<td>ECOS</td>
<td>ESA Costing Software</td>
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<tr>
<td>ED</td>
<td>Expansion Deflection</td>
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<tr>
<td>EH3C</td>
<td>Electrically Heated Curved Cooling Channel</td>
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<tr>
<td>EHT</td>
<td>Electrically Heated Tube</td>
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<tr>
<td>ELDO</td>
<td>European Launcher Development Organisation</td>
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<td>EMI</td>
<td>Electromagnetic Interference</td>
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<tr>
<td>EN</td>
<td>European Norm</td>
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<td>EPC</td>
<td>Etage Principal Cryotechnique</td>
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<td>EPS</td>
<td>Etage à Propergols Stockable</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>ESS</td>
<td>Emergency Stop System</td>
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<tr>
<td>FLACS</td>
<td>Flame Acceleration Simulator</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<td>FLAMAL</td>
<td>Product Name for Ethene (C2H4)</td>
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<tr>
<td>FLP-106</td>
<td>FOI Liquid propellant number 106 (ADN based monopropellant)</td>
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<td>FLPP</td>
<td>Future launcher Preparatory Program</td>
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<td>FOI</td>
<td>Swedisch Defence Reasearch Agency</td>
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<td>FOLAN</td>
<td>Forschung für Lagerfähige Antriebe (Research for Storable Propellants)</td>
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<td>FOS</td>
<td>Forschungsvorbung Oberstufe (Upper Stage Research Network)</td>
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<td>Framework Programme 6 (European Union Research)</td>
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<td>FP7</td>
<td>Framework Programme 7 (European Union Research)</td>
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<td>FSCD</td>
<td>Flow Separation Control Device</td>
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<td>GCH4</td>
<td>Gaseous Methane</td>
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<tr>
<td>Gehe</td>
<td>Gaseous Helium</td>
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<tr>
<td>GH2</td>
<td>Gaseous Hydrogen</td>
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<tr>
<td>GN2</td>
<td>Gaseous Nitrogen</td>
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<tr>
<td>GOX</td>
<td>Gaseous Oxygen</td>
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<td>GRASP</td>
<td>Green Advanced Space Propulsion</td>
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<tr>
<td>H2</td>
<td>Hydrogen</td>
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<tr>
<td>H2O2</td>
<td>Hydrogen Peroxide</td>
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<td>HAN</td>
<td>Hydroxyl-Ammonium Nitrate</td>
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<td>HARCC</td>
<td>High Aspect Ratio Cooling Channels</td>
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<td>HBE</td>
<td>Herschel-Bulkley Equation</td>
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<td>HCF</td>
<td>High Cycle Fatigue</td>
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<td>HF</td>
<td>High Frequency</td>
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<td>HNO3</td>
<td>Nitric Acid</td>
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<td>HotGaF</td>
<td>Hot Gas Test Facility</td>
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<td>HP-UX</td>
<td>Hewlett Packard UniX (Operation System)</td>
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<td>HTE</td>
<td>High-Thrust Engine</td>
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<tr>
<td>HTPB</td>
<td>Hydroxyl Terminated Polybutadiene</td>
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<tr>
<td>IMS</td>
<td>Integrated Management System</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<td>ISO</td>
<td>International Standard Organisation</td>
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<td>LH2</td>
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<td>LIBS</td>
<td>Laser Induced GAS-Breakdown Spectroscopy</td>
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<td>LIS</td>
<td>Laser Ignition System</td>
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<td>LOX</td>
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<td>MASCOTTE</td>
<td>Montage Autonome Simplifié pour la Cryocombustion dans l’Oxygène et Toutes Techniques Expérimentales</td>
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<td>MCC</td>
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<td>MCO</td>
<td>Maintien en Condition Opérationnelle</td>
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<tr>
<td>MMH</td>
<td>Monomethylhydrazine</td>
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<tr>
<td>MON</td>
<td>Mixed Oxides of Nitrogen</td>
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<tr>
<td>MoU</td>
<td>Memorandum of Understanding</td>
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<tr>
<td>MTBF</td>
<td>Mean Time before Failure</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>MTBR</td>
<td>Mean Time between Removals</td>
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<tr>
<td>MTTB</td>
<td>Mean Time to Breakdown</td>
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<td>N2O4</td>
<td>Dinitrogen Tetroxide</td>
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<td>NASA</td>
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<td>NCR</td>
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<td>Neodymium-doped Yttrium Aluminium Garnet (Laser)</td>
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<td>NE-X</td>
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<td>O2</td>
<td>Oxygen</td>
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<tr>
<td>OH</td>
<td>Hydroxyl Radical</td>
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<td>OMS</td>
<td>Orbital Maneuvering System</td>
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<td>ONERA</td>
<td>Office National d’Études et de Recherches Aérospatiales</td>
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<tr>
<td>PAL</td>
<td>Propulseurs d’Appoint à Liquides</td>
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<td>PIV</td>
<td>Particle Image Velocimetry</td>
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<td>PSP</td>
<td>Pressure Sensitive Paint</td>
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<tr>
<td>q2D</td>
<td>quasi two-dimensional</td>
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<tr>
<td>RA</td>
<td>DLR - Institut für Raumfahrtantriebe</td>
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<tr>
<td>RAID</td>
<td>Redundant Array of Independent Disks</td>
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<tr>
<td>RBCC</td>
<td>Rocket-Based Combine Cycle</td>
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<td>RCS</td>
<td>Reaction Control System</td>
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<td>REST</td>
<td>Rocket Engine Stability Research Initiative</td>
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<td>RFQ</td>
<td>Request for Quotation</td>
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<td>RMS</td>
<td>Root Mean square</td>
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<td>ROF</td>
<td>Ratio Oxydizer Fuel</td>
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<td>RP-1</td>
<td>Rocket Propellant 1</td>
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<td>SCC</td>
<td>Stress Corrosion Cracking</td>
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<td>SCORE-D</td>
<td>Stages Combustion Rocket Engine Demonstrator</td>
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<td>SEP</td>
<td>Société Européenne de Propulsion</td>
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<td>SFB</td>
<td>Sonderforschungsbereich (Collaborative Research Centre)</td>
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<td>SNECMA</td>
<td>Société Nationale d’Etude et de Construction de Moteurs d’Aviation</td>
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<td>SST</td>
<td>Stage Simulation Tank</td>
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<td>TAU</td>
<td>DLR Inhouse CFD Tool (Proper Name)</td>
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<tr>
<td>TCP/IP</td>
<td>Transmission Control Protocol / Internet Protocol</td>
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<td>TD-B</td>
<td>Technology Demonstrator B (Gel)</td>
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<td>TEKAN</td>
<td>Technologieprogramm Kryogene Raketenantriebe (Technology Program Cryogenic Rocket Propulsion)</td>
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<tr>
<td>TMF</td>
<td>Thermomechanical Fatigue</td>
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<td>UMS</td>
<td>Utility Management System</td>
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<td>TTZ</td>
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