Institute of Space Propulsion
Lampoldshausen

Status Report 2011-2017

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Cover Image: LOX/CH₄ test at test bench P3.2.
Institute of Space Propulsion
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Status Report 2011-2017
DLR Lampoldshausen – Meeting the Demands of Europe's Spaceflight Program

Space flight provides enormous benefits for scientific development and everyday life on earth. The fact is, it goes unnoticed by most people although space flight and its fundamental research and services mean that everyone can profit from the achievements of our modern society. Securing Europe's access to space is crucial if Europe is to continue to play a leading role in space exploration and scientific progress. The further development and operation of the European Launcher Family is therefore vital.

The German Space Strategy, published on 1st December 2010, clearly highlights 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 obligations within the European Launcher Community, namely systems responsibility for the old and new Ariane upper stages, will be fulfilled.

In as early as 1959 Lampoldshausen started working very closely with the major French organizations involved in space propulsion and the Ariane programs. This teamwork is of fundamental importance to the success of current and future European launcher development projects.

The space company ASL also has a division on the premises. In addition, various other companies and organizations make use of the site's services and test benches, thus contributing to cooperation on the basis of a close-knit and mutually beneficial alliance. These include the European Space Agency (ESA) and the French Space Agency Centre National d'Études et de Recherches Spatiales (CNES).

All of Lampoldshausen’s research and development programs directly support European rocket engine development programs. Lampoldshausen has long been the main European 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.

At present and in the near future Lampoldshausen is dedicated to supporting Europe's Ariane 6 program and as such the development of the new upper stage with the 180 kN, re-ignitable engine Vinci. High-altitude testing is mandatory and represents a major core competence in Lampoldshausen.

All critical components and operating procedures for the new Vinci upper stage engine 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.

The completion of the new Upper Stage Test Facility will upgrade Lampoldshausen’s test portfolio; not only rocket engines but complete upper stages of rockets will then be certified in Lampoldshausen.

DLR Lampoldshausen is home to the Institute of Space Propulsion and its five key departments: Test Facilities, Engineering, Rocket Propulsion, Propellants and Safety & Quality.

In view of the fact that potentially hazardous facilities are in operation on 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 activities.

In recent years, DLR Lampoldshausen has evolved to become a modern service provider currently incorporating all testing phases, i.e. from the provision of test benches and the operation of engines to the recording and transmission of measurement data to the client.

The Institute of Space Propulsion is one of a kind with its departments of Engineering, Test Operations on the one hand and scientific research on the other. It is able to handle the early stages of a development project all the way to final qualification, i.e. of a certified rocket engine or stage. DLR Lampoldshausen can therefore proudly boast it is unique in that it is the only test site in the world which supplies research results from the early TRL 1 stage of an engine design through to full certification (TRL 9) of the product.

It is well known that over the next few decades all launch vehicles will use chemical rocket engines. The
The key technology is combustion, and it is generally understood in the scientific community that regulating and managing 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 balance out. While the application of CFD or Computational Fluid Dynamics and other improved modelling techniques used in connection with compressor and turbine development paved the way to minimizing expensive testing, keeping combustion phenomena under control is still for the most part based on empirical analysis. 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 true 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.

In addition to the unique features required by high altitude testing and cryogenic technology for the development and qualification of space propulsion systems, DLR Lampoldshausen develops and manages the application of storable and gel propellants. The Institute for Space Propulsion coordinates the scientific and technical activities of the German Gel Technology Program. Over the last decade the search for rocket fuels (so-called “green propellants”) has been intensified to replace toxic products like hydrazine (see REACH). For this reason DLR Lampoldshausen has added research in this field to its list of priorities.

The training of space engineers and scientists plays a major role in ensuring reliable, long-term support of European engine development programs. In 2005 DLR Lampoldshausen set up its DLR_School_Lab to address this important factor, a laboratory for young people where promising future generations of researchers conduct experiments under the guidance of experienced scientists and engineers. By implementing the DLR_Campus Lampoldshausen a further asset in the education and training of bachelor, master and Ph.D. students has been created. Developing the Campus into one of the main sources of qualified personnel for the European Space Industry is another important goal of the Institute.

The Technology Transfer Center (TTZ) is a conglomerate of various regional business associations which, together with DLR Lampoldshausen, helps to improve the network of regional companies active in the field of science and industrial production. Clearly defined synergies involving 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 industry. The “H2ORIZON” project has been initiated making use of Lampoldshausen’s hydrogen infrastructure to foster technology transfer as regards regenerative energies.

Over the course of the last six decades, DLR in Lampoldshausen has maintained its position amongst the forerunners in the European space flight program. Together with its partners in the aerospace industry, the European Space Agency, the national agency, top research organizations and universities world-wide, the team in Lampoldshausen is making a vital contribution to developing and improving European rocket propulsion systems and ensures the continuous success of European operational launchers.

The DLR Institute for Space Propulsion in Lampoldshausen draws on competence and experience to deliver qualified R&D results.

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1. Research and Technology

Programmatic guidelines govern research and technology development activities focused on space propulsion at DLR. The purpose of the work carried out is to contribute to national requirements and to improve international competitiveness. Working on developing expertise in space propulsion technology is crucial in order to improve reliability, reduce costs in all phases of the product life cycle and to support environmental legislation. Key elements in this context are technologies for re-usable rocket engines, methane as a substitute for liquid hydrogen in cryogenic engines, upper stage technologies, and adequate green propellants capable of replacing the storable propellants commonly used today.

The main emphasis in liquid propellant rocket engine research and technology is on propellant injection, propellant combinations and combustion, heat transfer and cooling of structures under high thermal loads, and also the increase of supersonic expansion in the nozzle extension. Manufacturing techniques and material properties have a significant effect on the performance of a rocket engine. Components and features of a regeneratively cooled combustion chamber are illustrated in Figure 1.01.

The following are general objectives providing the orientation for further research in cryogenic liquid rocket engines:

- understanding the dynamics of fluid, physical, chemical, and thermo-dynamical processes in thrust chambers
- generation of quantitative data sets for the validation of models and CFD codes
- development of validated numerical tools for design justification
- prediction ability for engine performance with the aim of creating a „Virtual Engine“
- screening of new technologies for application up to TRL 5
- know-how transition from research to full scale testing.

Research into engine technology with advanced propellants covers the following:

- Investigation of the scope of application of used, known and new energetic materials for rocket, satellite and ramjet propulsion systems
- Understanding the fluid dynamical, physical, chemical, and thermodynamical processes in thrust chambers for the spectrum of different propellants
- Investigation of materials and components compatibility and durability with regard to their applicability in thrust chambers, tanks and feeding lines
- Use and enhancement of intrusive and non-intrusive diagnostic tools and techniques as support for research and development activities
- Development of concepts for a safe handling of new energetic materials with regard to their application in propulsion systems.

1.1 Engine Cycle Analysis

The development of new liquid rocket engines or the enhancement of models currently available requires a precise knowledge of engine parameters in stationary and transient operating conditions. These parameters determine not only the conditions under which individual engine components must work but also determine whether a given engine can satisfy the requirements set by an envisaged application.

Figure 1.01: Sketch of an axial section of a regeneratively cooled combustion chamber.
Fully understanding how components interact is vital before moving on to working on complete systems. Knowledge of component performance is necessary but not sufficient to master engine behavior. The Department of Rocket Propulsion is therefore developing expertise on rocket propulsion systems by investing in experimental activities and model development of engine components. Stationary engine cycle analysis plays a critical role in predicting the steady-state performance of future engines and in the detailed analysis of engines currently available. Using this method, the impact of new component technologies on the engine performance is evaluated. Examples of these new engine component technologies will be presented in the following sections. Cycle analysis essentially is the link between technological development of components and performance impact on engines, which directly affects the design of the stage and the launcher.

Transient engine cycle analysis concentrates on understanding the dynamic behavior of complete rocket engines during the transient phases, such as start-up, shut-down and throttling. Potentially dangerous modes of operation during these critical phases are identified by using transient engine cycle analysis. For this reason the engine is treated as a network of components and pipes, each behaving on a different time scale. Mastering the prediction of transient engine behavior is just as relevant in engine operation as in ground testing.

Methods and Tools

The commercially available software package called EcosimPro is used for steady state and transient cycle analysis in conjunction with the ESPSS library. This library contains models of various rocket engine components for liquid, hybrid and electrical propulsion. EcosimPro was developed in close cooperation with ESA. The validation and improvement of the models contained in the ESPSS library is in progress at DLR Lampoldshausen. The vast quantity of experimental data available at DLR Lampoldshausen is used to validate existing models or to develop and implement improved models for the engine cycle analysis. The models employed here need to be of low order to allow for a short computation time per cycle variant under investigation. The reduced accuracy of these correlations is improved by validation against the extensive reservoir of existing experimental data. This means that parametric studies can be conducted.

Project LUMEN – Applied Cycle Analysis

The LUMEN (Liquid Upper stage deMonstrator ENgine) project focuses on developing and testing a complete engine cycle of the expander-bleed type for test bench operation only. The final decision given the many possible variants of this basic cycle layout was supported by a trade-off study based on the stationary cycle analysis. The schematic of the chosen cycle layout – as modelled in EcosimPro – is shown in Figure 1.02. In addition, stationary cycle analysis serves as a method of “book-keeping” of the energy balance of the cycle, making sure that the target operating points are achieved. It provides the designers of the individual components with given ranges of input parameters and required output parameters to be met by the component. The overall analysis of the whole engine cycle is constantly and repetitively updated producing more accurate predictions of the individual components’ performance.

Figure 1.02: LUMEN expander-bleed cycle as modeled using EcosimPro/ESPSS

A refined model is used for the prediction of the transient behavior of the LUMEN bread-board engine. In addition to the steady-state behavior of individual components, their transient behavior also serves as an input for this model. The goal of the refined transient model is to identify potentially hazardous modes of operation and define sequences for valve settings to avoid dangerous routines during the transient phases. For the envisaged target cycle type – the expander-bleed cycle – the behavior as regards timing is dominated by two major components: the turbomachines and the cooling channels. The impact of the cooling channel design on the start-up behavior of an expander based cycle is examined and the
results are supported by data obtained in multiple hot-fire test campaigns.

**Hybrid Lunar Missions**

Another project is concerned with the opportunities that engine cycle analysis offer on the one hand and combining them to optimize mission trajectory on the other. The objective is to develop an application as a low-cost approach for lunar missions. EcosimPro/ESPSS contains the examination results of several stages – including lunar descent and ascent stages based on hybrid propulsion – using dedicated models for hybrid components. These engine level calculations are interlaced within ASTOS, a trajectory optimization tool generally available for commercial usage. Detailed information about hybrid engine operational behavior (e.g. propellant regression rate) is gathered in an inter-departmental effort at the M11 test bench.

**Dual-Bell Nozzles and their Impact on Launcher Performance**

How to link engine cycle and launcher trajectory studies and technological innovations on the component level was demonstrated within the context of an application of dual-bell nozzles in the Vulcain 2 engine. Several investigations were conducted to quantify the potential payload gain when using dual-bell nozzles. For this purpose an assortment of Vulcain 2 extension contours were designed. The two variation parameters were the starting point and the inflection angle of the nozzle extension. Taking these parameters into consideration an analytical and a numerical method were applied to predict the impact of the dual bell nozzle on the payload mass. The numerical approach was conducted applying TOSCA-TS, DLR’s trajectory simulation code (Figure 1.03). Both calculation procedures produce a good match in the results and the payload gain into geostationary transfer orbit was evaluated to be up to 490 kg.

**1.2 Propellants**

The interest in advanced and green propellants has significantly increased in the last two decades and extensive research and technology development activities in this field can meanwhile be observed worldwide. In earlier times only the classical demands on propulsion systems like higher thrust, longer flight distances, higher velocities, etc., together with the well-known request of cost reduction, were important. The development of propulsion systems will in the future be more and more influenced by other requirements concerning more complex missions, higher safety and environmental friendliness, but of course also by cost reduction aspects.

In 2006 the European Union introduced the REACH regulation (Regulation, Evaluation, Authorization and Restriction of Chemicals) with the aim of identifying and restricting the use of substances, which are dangerous for the environment and health. Hydrazine, the standard monopropellant for orbital thrusters in the last 50 years, was added to the REACH candidate list of “Substances of Very High Concern” (SVHC). It is to be expected that also the use of hydrazine derivatives (i.e. UDMH and MMH), in hypergolic propellant combinations will be restricted in the future. Limits could also be set mid-term as regards ammonium perchlorate, the most commonly used oxidizer in composite solid propellants. Thus wide-ranging research and development activities are necessary to create suitable propellants with a reduced hazard potential (i.e. toxicity, carcinogenity, etc.) and lower life-cycle cost compared to traditional propellants. Unconventional solutions are needed to meet the new requirements.

The emphasis of the research and development activities carried out at the M11 test complex is on innovative energetic substances and the extension of the current application ranges of common energy-efficient materials for rocket, satellite and ramjet propulsion systems both for the civil and security-related sector. Of course there is a desire for future propellants with a significantly reduced hazard potential. In addition, their performance should be equal to or even better than today’s standards and they should be easier to handle in comparison to hydrazine(s).
The search for gelled propellants and advanced green propellants replacing hydrazine and propellant combinations with hydrazines and its derivates is high on the list of priorities. Great effort is put into investigating and determining the properties of materials and components for use in thrust chambers, storage devices and feeding systems. Intrusive and non-intrusive diagnostic tools and techniques are used and adapted to carry out this task. An important aspect in this context is also the work involved on the safe and environmentally friendly handling of the new energetic materials under investigation as in the preparation for future engine development and qualification testing at DLR test facilities and in industry.

In order to fulfill the need for greener and safer future propulsion systems research and development activities are being conducted in the following areas:

- Identification and engine process development of advanced green storable monopropellants for the replacement of hydrazine in orbital propulsion systems. ADN-based monopropellants and nitrous oxide based mixtures are currently under detailed investigation. In order to achieve this goal, the individual processes such as material compatibility, atomization, ignition and combustion are studied.

- Engine process enhancement with gelled propellants which combine the advantages of propulsion systems with liquid and with solid propellants. Investigations cover gelled propellants with advanced compositions and ingredients, combustor process, rheology, flow and spray behavior.

- Enhancement of hybrid rocket engine performance. This task includes looking deeper into the combustion processes of solid fuels with high regression rates.

- Identification and engine process development of storable bipropellant mixtures as a mid-term replacement for MMH und UDMH. Highly concentrated H$_2$O$_2$ is one of the candidate oxidizers in connection with distinct ionic liquids as fuel. This work is currently in an initial stage of being set-up.

- Operation of the M11 test complex and the physico-chemical laboratory for R&D tasks and contracting.

- Operation of the M11.5 Research and Student Test Field for individual research activities and for education purposes of students, e.g. within the STERN program.

These research activities at Lampoldshausen cover various tasks, but nevertheless have similarities with the treatment of sub areas like research on flow or spray behavior. Figure 1.04 shows in which sub areas activities are currently ongoing. Also this diagram gives references as to where further information is available in this report.

![Figure 1.04: Sub-working areas for advanced propulsion system types.](image)

The ongoing basic experimentation activities into transpiration cooling focus on a Scramjet channel, but are also relevant for high temperature thrust chamber flows with advanced and conventional propellants. These activities are described in this report in chapter 1.6 “Heat Transfer and Cooling”. As regards combustion stability, sufficiently stable operation has been identified for distinct propellants. In addition work on liquefying fuel layers was carried out for hybrid motor processes.

It is important to note that there doesn't exist only one propellant and only one engine type that suits all propulsion applications. Instead there are different mission types and thus different demands for the engines. That new propellants should meet the requirements for greener and safer transportation systems is obvious. Figure 1.05 shows theoretical specific impulse $I_{sp}$ ranges and typical thrust classes of
propellant types under investigation at Lampoldshausen.

![Figure 1.05: Overview of performances and typical thrust classes for the propellants classes currently investigated at Lampoldshausen. Theoretical values of $I_{sp}$ are from NASA CEA, $p_c$: 20 bar, $\varepsilon$: 40, frozen at the throat.](image1)

Gel Propulsion

Gelled propellants and their specific properties are of interest for both rocket and ramjet applications due to the simplicity of implementing a variable “on-demand” thrust control, easy handling and improved operational safety. The beneficial combination of performance flexibility and storage characteristics merges the major advantages of liquid and solid propulsion systems and is mainly caused by the typical non-Newtonian flow behavior. Table 1 shows a comparison of the properties of different rocket propulsion system types. It is obvious that gel rockets and hybrid rockets are advantageous for missions where throttle ability and safety are of primary interest.

During the gelation process a 3D net-like structure is formed by a gelling agent in which a liquid – either a monopropellant, a fuel or an oxidizer – is embedded. The gelled fluid behaves like a solid at rest. If a sufficiently high shear stress is applied to the gel, the 3D-mesh of the gel is destroyed and the gel becomes more and more liquefied.

At very high shear rates, typically reached during the propellant injection processes, the properties of the gelled liquid become similar to the properties of a pure liquid itself. Thus, the advantages of liquid and solid propellants can be combined.

![Figure 1.06: Hot fire test at test position M11.4. The main goal of the research and technology development work for gel propulsion is to obtain detailed knowledge of the processes within the combustion chamber, injector and feeding lines. This facilitates the realization of a reliable design process for future gel rocket engines with high power densities and stable operating envelopes. The cost can therefore be kept to a minimum and the test requirements reduced. These activities are predominantly part of the “German Gel Technology Program”, of which the DLR Institute of Space Propulsion also coordinates the scientific/technical activities, and the internal projects ITEM-FK, GGeRA and RFR.](image2)

Gel Propellant Development

Gelled monopropellants consist of two or more components namely the (liquid) propellant blend, a gelling agent and partly also certain additives. Over the last few years, the focus was set on non-toxic monopropellants in combination with energetic gelling agents that burn largely signature-free and do not leave any deposits. Gels which feature both high performance and good delivery characteristics at acceptable storage and safety specifications were developed and tested within model combustors at the M11.4 test position. An image of a typical test run with a low signature gel propellant is shown in Figure 1.06.
Solid | Liquid storable | Liquid cryogenic | Slurry | Hybrid | Gel
--- | --- | --- | --- | --- | ---
Throttleability | — | ✓ | ✓ | ✓ | ✓ | ✓
Defined engine shut-off | — | ✓ | ✓ | ✓ | ✓ | ✓
Reignitability | ± | ✓ | ✓ | ✓ | ± | ✓
Simple handling | ✓ | — | — | — | ± | ±
Simple storability | ✓ | ✓ | — | — | ± | ✓
Increase energy content by energetic particles | ✓ | — | — | ✓ | ✓ | ✓
Not sensitive against:
Accidental ignition | — | ✓ | ✓ | ✓ | ✓ | ✓
Leakages | ✓ | — | — | — | — | ✓
Impact, friction, electrical discharge | — | ✓ | ✓ | ✓ | ✓ | ✓
Cracks (Propellant grain) | — | ✓ | ✓ | ✓ | ✓ | ✓
Sedimentation of particle additives | ✓ | — | — | — | ✓ | ✓
Boil-off | ✓ | — | — | — | ± | ±
Fuel movement, sloshing in tank | ✓ | — | — | — | ± | ±

Table 1: Selection of properties, where gelled propellants offer advantages.

Bipropellants and especially green hypergolic systems are gaining a greater focus of attention, which could lead to a further improvement in their performance, simplifying the ignition process and leading to opportunities for new applications. Reasonable performance standards, production, handling and treatment properties must exist or must be developed regarding the selection of suitable gel propellant compositions. The physico-chemical laboratory is authorized and able to safely produce and handle the required gelled propellants on a test bench-scale (i.e. several kilograms at once).

Rheological Properties and Flow Behavior

For the development of gel propulsion systems a very detailed knowledge of non-Newtonian rheological and physical properties and of the flow and spray behavior is an essential basis. The processes are more complex than in Newtonian propellants and the corresponding research activities required are therefore very intensive. The three most relevant aspects of the rheology of a gel are the shear thinning behavior, the upper Newtonian plateau and the yield stress. The dependency of the shear viscosity versus the shear rate for a typical gelled fuel can be seen in Figure 1.08.

![Figure 1.07: Examples of gelled fuels](image)

![Figure 1.08: Dynamic shear viscosity vs. shear rate for a JetA-1/ThixatrolST gel.](image)
This shear-thinning behavior can be described by the so called Herschel-Bulkley Extended (HBE) equation which was evolved and verified at the Institute.

\[
\eta = \frac{\tau_0}{\dot{\gamma}} + K \cdot \dot{\gamma}^{n-1} + \eta_\infty
\]

The quantitative dependence of the dynamic shear viscosity \( \eta \) from the shear rate \( \dot{\gamma} \) is described for the whole propulsion relevant range of shear rates \( 10^{-2} \text{ s}^{-1} < \dot{\gamma} < 10^6 \text{ s}^{-1} \) with sufficient accuracy, whereas \( K, n, \tau_0, \text{ and } \eta_\infty \) are material dependent parameters.

Numerous hot fire tests were conducted with a gelled monopropellant using a model combustion chamber with an inner diameter of approx. 21 mm (BK21). During the search for the optimum ratio of combustion chamber volume and nozzle throat area, also known as the characteristic length \( L^* \) of the combustor, the combustion chamber length was systematically reduced from 400 mm down to 80 mm. This is equivalent to a variation of \( L^* \) between 1 m and 7 m taking into account the different nozzle configurations applied. A point of self-sustaining combustion was found for the initial test configuration at \( L^* = 7 \text{ m} \) and approx. 30 bar as well as for very small characteristic lengths of about 1.3 m when operated at 40+ bar. As depicted in Figure 1.10, the maximum combustion efficiency of BK21 has been achieved for a characteristic length \( L^* \) of 1.5 m to 2 m which equals a chamber length of 150 mm up to 180 mm. In comparison, hot fire tests with the larger BK50 with an inner diameter of 50 mm showed generally lower combustion efficiency with an optimum characteristic length of approx. 7.5 m but with a more extensive operational pressure range. This finding offers a trade-off between either compact high performance combustors or motors with excellent controllability and operational envelope depending on the designated mission.

Figure 1.10: Combustion chamber performance with respect to chamber geometry for the small inner diameter combustion chamber BK21

While experiments regarding spray behavior were in the past mainly performed at ambient or low pressures the research into combustion related spray
formation will take place under levels of high pressure. Preliminary tests already demonstrated the feasibility and the benefits of a visual examination of the gel injection and combustion process using e.g. shadowgraph techniques (see Figure 1.11). Experiments with a model combustor featuring optical access are ongoing. This means that for the first time a detailed analysis and insight into the chamber processes will be possible for the investigated gelled propellants.

![Figure 1.11: Model combustor with large windows. Bottom: Row of images from a hot fire pretest of a combustion chamber with optical access.](image)

**Energetic Ionic Liquids (EILs)**

Ionic liquids are defined as salts with melting points below 100°C and whose melts are composed of discrete ions. In the space propulsion community also energetic salt solutions are rated as Energetic Ionic Liquids (EILs). One of the most promising candidates for propulsion applications is ammonium dinitramide (ADN, NH$_4$[N(NO$_2$)$_2$]), which has a very high solubility in e.g. water. Due to the fact that salt solutions cannot completely be rated as ionic liquids, we would rather refer to them here in the context of ADN-based propellants. ADN was originally developed as an oxidizer for solid rocket propellants.

Over the last two decades, liquid monopropellants based on ADN were developed and are now considered as possible substitutes for monopropellant hydrazine.

The research is focused on two ADN-based monopropellants: i.e. LMP-103S (a solution of ADN in water, methanol and ammonia) and FLP-106 (ADN in water and monomethyl formamide MMF). These propellants are less toxic than hydrazine: they are not carcinogenic, they can be handled without SCAPE (Self-Contained Atmospheric Protection Ensemble) suits and LMP-103S can be shipped by plane. A photo showing the complexity of hydrazine fueling is shown in Figure 1.12. It illustrates the complexity of hydrazine fueling. The reduced hazard potential simplifies the handling and reduces the overall life cycle costs.

![Figure 1.12: Hydrazine fueling. For the operation SCAPE suits are required.](image)

![Figure 1.13: ADN-based monopropellant FLP-106. The handling is much easier compared to hydrazine.](image)
Both propellants have higher specific impulses than hydrazine and also a higher density. Experiments with LMP-103S by ECAPS during the PRISMA satellite mission have already shown that it is used successfully in space. The specific impulse measured was 8% higher and the density specific impulse was 32% higher compared to hydrazine. ECAPS is currently supplying propulsion systems for Terra Bella’s SkySat satellites, to be used for earth observation. The first of these satellites was launched in 2013. LMP-103S is also in the qualification process at ESA for use in connection with the Myriade Evolution platform.

Lampoldshausen started to work on these propellants in 2009. DLR participated from 2009 to 2012 in the FP7 project GRASP, funded by the European Community. A test bench as shown in Figure 1.14 was set up to conduct durability and compatibility testing of a flow control valve (FCV) with FLP-106. This type of valve controls the propellant flow from the tank inside a satellite to one of the small attitude control thrusters. Hot fire tests were conducted using two demonstrator thrusters designed by the Austrian research company FOTEC.

![Figure 1.14: Setup for testing durability and compatibility of a FCV with FLP-106.](image)

The research on ADN-based monopropellants is a joint team effort within the frame of EU H2020 project Rheform, involving six other European industrial partners and research centers. This project was initiated in 2015 and is ongoing until 2017. Its main goal is to develop technologies for use with green propellants. The atomization ambient (flashing) and under vacuum near conditions of ADN-based propellants and other solutions has been investigated in detail and the main results are presented in chapter 1.3.

Research on the ignition of ADN-based propellants is ongoing. The related thrusters are ignited with a preheated catalyst. A cold start is not possible: the decomposition sets in only if the catalyst has reached its operational temperature (around 350°C). This limits the use of ADN thrusters as compared to hydrazine models: the catalysts currently used for hydrazine can be started from a cold state, even if preheating is often used to increase the lifetime of the catalyst.

Cold start capability could be important if the thruster has to be used in an emergency situation, where there is no time to pre-heat it. Being able to reduce the necessity for preheat power would also be of benefit in the case of small satellites, where the available power supply is limited. The preheating power needed for larger hydrazine thrusters remains limited to the range of a few tenths of Watts. On the other hand the preheating power requirements for ADN catalysts increase strongly for larger thrusters. This is due to the fact that most of the power is used to evaporate the propellant and the propellant mass flow rate increases almost in line with the thrust. In the Rheform project two parallel research activities are being conducted on ignition: one on the development of a new catalyst requiring a lower preheating temperature, the other as regards the development of a thermal igniter for ADN-based propellants. The work on thermal igniter is taking place mainly at Lampoldshausen, and the main results are described in chapter 1.4.

Another on-going project on ADN is EQUAD. This collaboration with the Meissner Company focuses on the development of a new and less expensive synthesis process for ADN.

Not only the liquid state of EILs is interesting for propulsion applications but also gelled ionic liquids have advantages concerning throttle characteristics, good storage capabilities, easy handling features and reduced risk regarding human and environmental exposure. First spray and combustion tests with ADN-based oxidizer gels were carried out several years ago for bipropellant gel rockets and will continue in 2017. Working hand-in-hand with the Fraunhofer-Institute of Technology (ICT) has proved very successful. Activities focus in this case on the further develop-
ment and investigation into innovative energetic ionic liquids for propulsion applications. Several varieties are interesting due to their good theoretical performance parameters. Scaling up production quantities is planned so that they can be tested in future at M11. A joint patent application for an almost water-free ADN-based EIL is on the way and this ADN-based monopropellant is not restricted by any patent rights.

**N₂O-Based Monopropellants**

In addition to research and development activities on ADN-based energetic ionic liquids, efforts are being carried out on mixtures of nitrous oxide (N₂O, also called dinitrogen monoxide) with hydrocarbons. Such nitrous oxide based combustible energetic mixtures (NICEMs) are interesting candidates to replace hydrazine. They offer significantly higher specific impulses > 300 s than ADN-based EILs. A mixture consisting of N₂O and ethene (C₂H₄) was chosen to be used as a premixed monopropellant and was given the name “HyNOx” (Hydrocarbons mixed with nitrous oxide).

The work concerning this monopropellant is part of DLR’s “Future Fuels” strategic project, a general description of which can be found in chapter 4.1.1.7. References to the work packages focusing on the research of N₂O-based propellants can be found later on in several sub-chapters.

Ethene was chosen due to its vapor pressure being comparable to nitrous oxide (at 273°K: C₂H₄: 41 bar; N₂O: 31.2 bar). This similarity should ensure good miscibility and simultaneous evaporation in the tank.

The hydrocarbon / nitrous oxide mixture used offers a significantly higher specific impulse \( I_{sp} \) than conventional monopropellants or other green alternatives. (approx. 319 s vacuum \( I_{sp} \) for N₂O/C₂H₄ compared to 240 s for hydrazine or about 250 s for ADN-based propellants). This pre-mixed monopropellant can deliver \( I_{sp} \) similar to a bipropellant, which makes it particularly interesting due to the expected reduction of structural weight.

Testing at DLR went very well and the mixture proved to be economic and reliable with positive re-ignition characteristics, all of which make it a good candidate for implementing in future thrusters. In contrast, several challenges in dealing with the propellant mixture exist. One main task for a safe handling of the premixed oxidizer and fuel and to raise the system’s TRL involves avoiding flame flashback which could cause significant damage across the injection system in the feeding lines or tank structures. More research into flashback characteristics during combustion and ignition is therefore required. To study different flame arresting elements, injectors and the ignition process, a separate test set-up was built and put into operation.

A second challenge the mixture presents is the high combustion temperature. The laws of physics dictate that a high \( I_{sp} \) correlates with high combustion temperatures. An active cooling system requiring detailed knowledge about the occurring heat fluxes is essential. Thus the applied heat loads and the temperature development in the combustion chamber walls are studied in combustion tests and numerical analyses.

The highly flexible, modular combustion chamber and injection system used to investigate the characteristics of the propellant mixture is shown in Figure 1.15. The chamber is equipped with ports for different ignition systems. Variable injection elements can be mounted and the length of the chamber can easily be altered by replacing or removing segments. Also various nozzles might be used.

![Figure 1.15: Sketch of the combustion chamber used for investigations on N₂O/C₂H₄ mixtures](image)

For safety reasons the HyNOx mixture is currently not stored in one tank, N₂O and ethane are mixed in their gaseous state upstream of the injector. This offers several advantages:

- Easy comparability to CFD simulations is possible; there are no evaporation effects of the liquefied propellant which have to be taken into consideration;
- The gaseous mixture is easier to ignite, and thus flashback is more likely to occur. By using a gaseous mixture a “worst case” approach is achieved for investigation into flashback phenomena.
The experiments were carried out in a container at the M11.5 test field. Figure 1.16 is a photo of a test run.

![Figure 1.16: Combustion test of a N2O/C2H4 mixture](image)

Research and development into HyNOx is conducted as part of the following work packages within the Future Fuels program:

- "Analysis of ignition methods and flashback arresting elements"
- "Investigation of heat flux during combustion tests"
- "General performance parameters of the propellant mixture" as described as follows.

From the analysis of the conducted combustion tests values of the experimental characteristic velocity $c^*$ were determined and compared to theoretical $c^*_\text{theo}$ obtained with the help of NASA CEA software. Figure 1.17 shows the $c^*$ efficiency, i.e. the ratio of experimental to theoretical $c^*$, for a nearly stoichiometric mixture in relation to the combustor pressure. As the combustor length and size are not optimal, the $c^*$ efficiency still increases with the increasing chamber pressure.

![Figure 1.17: Combustion efficiency vs. chamber pressure](image)

**Hybrid Rocket Propulsion**

Hybrid rockets (HR) have some advantages as compared to rockets with solid or liquid propellants. The interest in hybrid rocket engines is growing as seen in the increasing number of publications over the last few years. As regards storage and handling HR have zero TNT equivalent compared to solid propellants. This is an important aspect in determining the safety and total cost of an engine. Controllable thrust including shut-off and restart capability are further advantages. Less piping and valves due to the use of only one liquid component reduce the complexity and costs compared to set-ups for liquid rocket engines. Applications especially in space tourism like SpaceShipOne clearly demonstrate the potential of hybrid rocket engines. They might fit well in certain application areas where operational safety, shut-off and throttling are required. Their inherent safety makes them also attractive for educational activities with university students.

**Motivation**

Liquefying hybrid rocket fuels were discovered recently at Stanford University and the interest in them has strongly increased over the last years. The reason is that the regression rate of this kind of fuels is higher than that of conventional pyrolyzing polymeric fuels. In fact, the use of polymeric fuels, such as hydroxyl-terminated polybutadiene (HTPB) or high-density polyethylene (HDPE), shows relatively low regression rates which results in the necessity of multiport fuel grains for high thrust applications. The multiport design increases the residual mass of unburnt fuel and thereby decreases the obtained specific (total) impulse. Instabilities are also more likely with this type of design. On the other hand, cryogenic solid n-pentane shows regression rates 5-10 times higher than polymeric hybrid fuels. Compared to the same type of fuel the regression rate of paraffin-based fuels tested at Stanford University are 3-5 times higher for similar mass fluxes. This is achieved by a different combustion technique. Paraffin-based, liquefying hybrid fuels form a liquid layer on the fuel surface during the combustion process. The low viscosity and low surface tension of the fuel enable an additional mass transfer by entrainment of liquid droplets. The gas flow over the fuel surface, due to the high shear stresses induces instabilities in the liquid layer, which produce the droplet entrainment, see Figure 1.18.
Figure 1.18: Liquefying fuel combustion theory.

Figure 1.19: Liquefying fuel combustion image (oxidizer mass flow from left to right).

An image of this entrainment process of a liquefying paraffin-based fuel is shown in Figure 1.19. It was obtained with the optical combustion chamber setup at the M11.3 test position. The droplet entrainment can clearly be seen as well as the wave-like movement and liftoff of the flame along the fuel surface.

Previous research with this optical chamber focused on the visualization of droplet entrainment and the application of a monochrome Schlieren set-up to visualize density gradients and flow patterns during combustion.

**Paraffin-Based Hybrid Fuels**

Paraffin-based fuels belong to the class of liquefying fuels and are therefore characterized by the entrainment phenomenon.

The characteristics of four paraffin waxes with different viscosities in combination with gaseous oxygen were investigated. They are used in their pure form as well as in connection with different additives to modify their mechanical and rheological properties. All samples for the ballistic tests have been blackened by additives during production to limit radiation effects on the fuel surface during combustion. Generally, the amount of blackening additive was less than 2% and the impact on the performance is therefore negligible. Three different additives were chosen in order to investigate and improve the mechanical properties of the paraffin samples: stearic acid (SA), a nanoclay material from the manufacturer Byk and a commonly available polymer.

In-depth laboratory experiments were performed to measure the viscosity and surface tension of the different fuels. These are the two material parameters which are expected to have the biggest impact on the entrainment mass flow according to Figure 1.18. Tensile tests show significant improvement in maximum stress and elongation when polymers in low concentration are added to the paraffin samples. The viscosity of the fuels also increases significantly and this affects the droplets entrainment process during combustion as well as the regression rate.

Regression rate tests were carried out in a 2D radial micro burner at the M11.3 test. The regression rate values decrease as the viscosity of the paraffin samples increases. Figure 1.20 shows the results for the paraffin type 6805 in combination with different additives.

Figure 1.20: Regression rate results of paraffin 6805 with additives.

It was found that an exponential relation exists between the liquid fuel layer viscosity and the regression rate. This can be used to predict the regression rate of the new liquefying fuels by measuring their viscosity, see Figure 1.21.
The main areas of interest are the instability mechanism with its dependence on the viscosity of the liquid layer and the oxidizer mass flow (see chapter 1.5). Therefore optical studies including the recording of high-speed videos to capture the entrainment process were performed in a 2D slab burner configuration with windows on two sides.

The frequencies and the wavelengths of the waves induced on the liquid layer by the high-speed gas flow have been investigated.

High-speed video imaging is used during testing with up to 10,000 FPS frames per second to achieve high resolution and accuracy. Automated video data analysis routines have been developed in order to better compare the data with the test runs. This includes Proper Orthogonal Decomposition (POD) and Independent Component Analysis (ICA) techniques, whereby the flow dynamics of the combustion flame can be described in space and time.

1.3 Propellant Injection

Propellant injectors play a major role for the most part in the performance of rocket combustors. Independent of the system chosen for engine cycle and application injection for liquid propellant the general engine requirements are:

- acoustic and fluid mechanic decoupling of the combustion chamber from the propellant supply system
- homogeneous propellant distribution to individual injector elements
- controlled behavior during start-up transient to guarantee reliable and smooth ignition and flame anchoring
- stable combustion at transient start-up and steady state operation
- generation of minimum chemical loads on combustion chamber walls
- optimized heat flux levels regarding the chamber wall for the specific engine cycle.

Depending on the application there are additional requirements such as, for example, high throttle ability. All these requirements have to be met with minimal pressure loss and maximum combustion efficiency.

Despite being important as regards functionality the design of injectors is mainly based on empiric rules. The task of developing suitable models poses a special challenge due to the complexity and non-linearity of injection and combustion. Thus extensive validation procedures and testing is required. In parallel CFD-models are developed. In this case validating the results with experimental data is the key to success.

Injection Systems

Within the last decade the main focus of research into injection system technologies was placed on the identification and quantification of principal physical processes during transient start-up, ignition and steady state operation of rocket engines. Of specific interest was the impact of the thermodynamic state of the propellants such as sub-, near- and supercritical pressure and temperatures on atomization and spray formation, mixing and combustion. Besides using the propellant combination LOX/GH₂, research has been carried out into combining LOX/CH₄. The activities center on experimental research and technology validation investigations and on the development and validation of numerical design tools for design justification.

The key topics addressed with respect to propellant injection are:

- demonstration of the Advanced Porous Injector (API) technology
quantitative LOX-spray and flame characterization in hot fire tests for a single coaxial LOX/H₂-injection element
- injection of cryogenic fluids in a low pressure environment
- development and application of a structured approach for the design and validation process of components for research combustors.

**API Injector Concept**

The API (Advanced Porous Injector) is an innovative injection concept as shown in Figure 1.22. The fuel, e.g. hydrogen, is fed through a porous face plate into the combustion chamber. The oxidizer, liquid oxygen, is injected through tubes integrated in this porous faceplate. The API concept as a solution is promising as regards turbo-pump performance requirements when compared to classical coaxial injectors (low pressure loss in the injector head) and the manufacturing costs would be lower.

Atomization in coaxial injection elements depends on the velocity difference between the injected H₂- and LOX-flows, which requires high injection velocities for H₂ and therefore results in a correspondingly high pressure loss. Using the API atomization and mixing is driven by the combustion process inside the chamber.

Research into this novel injection concept concentrated first on verifying the injector layout driving mechanism for atomization in injecting LOX/H₂. The stability and combustion performance of API injectors were evaluated during parametric studies and included varying the injection conditions (velocity and momentum flux ratios of the propellants) and the thrust chamber related parameters (main flow Mach number, injector diameter, injector pattern). The studies were carried out systematically and resulted in a deeper understanding of the operational behavior and the potential scope of applications of this injection system.

A second development direction focused on possible applications for APIs looking at gas-generators, pre-burners, and RCS thrusters. The assembly of the BKI research combustor equipped with an API is shown in Figure 1.23. The API injector head was specifically designed for mixture ratios and fuel injection temperatures typical for pre-burner applications. The operation has been successfully demonstrated in a hot-fire test campaign at test bench P8 for pressures up to 330 bar.

The API has been benchmarked against a state-of-the-art industrial design of an injection head with coaxial injection elements. As part of the Propulsion 2020 cooperation activities a joint Airbus DS/DLR test campaign was carried out at P8. The injection elements of the injector head provided by Airbus DS were similar to those used in the Vulcain 2 engine. The campaign demonstrated that the API injector concept had a clear advantage in terms of combustion efficiency under nominal and even more so under off-design conditions, which is essential for applications which require throttling (see Figure 1.24).
The axial heat flux evolution in the chamber shows an earlier onset of high wall heat flux levels in the thrust chamber when equipped with the API as opposed to a head with classical injection elements. The API type of injector could significantly reduce the chamber length and therefore weight of any expander cycle based engine (e.g. Vinci).

The compatibility of the API concept with the new laser ignition technology (chapter 1.4) was proven in sub-scale tests at the M3.1 test bench. The API concept was tested under ambient and low-pressure, i.e. representative of ignition conditions in space in a RCS-scale thruster with LOX/H₂ and LOX/CH₄. The ignition system of this API injector was successfully demonstrated. The API concept together with a laser ignition system is the current baseline injector model for DLR Lampoldshausen’s LUMEN engine demonstrator (chapter 4.1.1.2).

Quantitative Characterization of a Single Coaxial Injection Element

Validation of numerical models predicting thrust chamber performance requires not only the availability of experimental data on global parameters such as combustion chamber pressure, but also detailed, quantitative information about the reactive flow in the combustor. DLR has the required know-how in the design of high pressure combustors with optical access. This expertise enables the application of imaging techniques which give access to the topology of the LOX spray and the flame extension inside the combustor. Especially the application of high speed cameras (up to 40 kHz) provides data sets with good statistics as well as the capability to resolve dynamic processes.
chapter 4: ProTAU), as well as the commercially available ANSYS/CFX code. Propellants where injected through a single coaxial injector element in the tests. Because the process is less complex the requirements as regards computational resources are less demanding and this allows for LOX jet and flame imaging in a quality that would not be possible in a multi-injector configuration. By fitting the test specimen and the bench with appropriate sensors precise data defining the boundary conditions in the simulations can be generated. To ascertain exactly what occurs during the atomization, mixing, and combustion processes shadowgraph and flame emission imaging was utilized. The test matrix was defined to cover operating conditions representative of industrial rocket combustion chambers and specifically to include load points at combustion chamber pressures $p_c$ below, near, and above the critical pressure of oxygen at $p_{\text{crit}}=5.04$ MPa.

Figure 1.26: Shadowgraph images at load points $p_c=6$ MPa/ROF=6 (top) and $p_c=4$ MPa/ROF=4 (bottom).

From the visualization data intact core lengths of the LOX jet and flame lengths according to the operating conditions were extracted (see Figure 1.26 and Figure 1.27). High speed imaging also gives access to visualizing dynamic features like the LOX jet velocity. Furthermore details of the phenomenology of LOX jet atomization were identified which provided reference data for a later validation of LES simulations of this test case.

Figure 1.27: OH images at load points $p_c=60$ bar/ROF=6 (top) and $p_c=40$ bar/ROF=4 (bottom).

Figure 1.28: Temperature distribution and stream lines of a TAU simulation of the BKC-test case.

Figure 1.29: Wall temperature profile of combustion for the BKC-test case. Comparison of experimental data with numerical results obtained with CFX.

Injection of Cryogenic Fluids in a Low Pressure Environment

Cryogenic upper stages and Reaction Control Engines are ignited under high altitude conditions. During the pre-ignition phase propellants are injected into a low pressure environment under the same conditions. Under low pressure conditions flash vaporization of the injected liquid propellants may occur depending on the specific ignition sequence and injection parameters. This phenomenon is relevant when filling the propellant domes as well as when propellant is injected into the combustion chamber. Both processes have an effect on the conditions inside the combustor at the time of ignition. The results of activities regarding flash evaporation are being used in the SFB Transregio 75 (chapter 4.1.2.2).

The main goals of the research are:

- Investigation into the conditions at which flashing occurs for liquid propellants used in space propulsion (LOX, green propellants).
- Characterization of the spray with optical diagnostics using high-speed shadowgraphic technology and Phase Doppler Anemometry.
- Generation of a data base for the validation of numerical models describing transient injection.

In a preparatory program of testing flash evaporation of LOX injected into a low pressure environment was investigated at the M3.1 test bench. Figure 1.30 shows the spray pattern for different pressure ratios $R_p=\frac{p_{\text{sat}}(T_{\text{inj}})}{p_c}$. The effect of the length of time the liquid is in the injector tube is clearly visible. For the long injector tube heterogeneous nucleation affects the formation of the spray, for the short tube
homogenous nucleation regulates the spray formation.

Reference data for code validation has to be generated under clearly defined experimental conditions. A new test set-up at the M3.3 test facility has been designed and is currently being implemented which allows a precise temperature adjustment of the injected liquids. Tests will start with LN$_2$ as the test fluid and will then carry on with liquid oxygen. A PDA-system will be provided as part of the TRR 75 project to measure local velocity and drop size distributions in the sprays. PIV will be applied to obtain two-dimensional velocity profiles. An upgrade of the set-up to enable flashing investigations of LCH$_4$ is being prepared.

Figure 1.30: preliminary studies of LOX Flash-vaporization at test facility M3.1: left: conf. 1 with L/D = 22, T$_{inj}$= 94 K (heterogeneous nucleation), right: conf. 2 with L/D = 1, T$_{inj}$= 113 K (homogeneous nucleation).

Figure 1.31: M3.3 test facility

**Design and Validation of an Injector Head for a Research Combustor**

The design requirements for components of research combustors have significantly increased in line with the progress made in numerical simulation capabilities. Code validation requires that experimental reference data be collected under well-defined boundary conditions. For that reason a new injector head has been designed for the research combustor D (BKD). The injection head of BKD has 42 coaxial injection elements which are distributed in three rings in the injection plane. The new injector head design has been optimized to achieve equal mass flow over each injector element.

Figure 1.32: Simulation of the pressure distribution in the LOX-domes with the old (left) and the new (right) designs.
The optimized design provides a homogeneous mass-flow distribution with deviations of no more than ±1.5% between the injection elements. The numerical design has been verified by comparison with water flow checks.

**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. Figure 1.34 shows typical shadowgraph images of the spray behavior of an ADN-based gel at high injection velocities.

Recently it was observed in tests with an impinging jet injector that the formation of droplets was prevented with certain gels. Instead elongated structures called threads or ligaments were formed, as shown in Figure 1.35. Despite the rheological curves of the shear viscosity vs. the shear rate for two selected gels with different gelling agents were nearly identical, thread formation occurred for the gel with a cellulose-derivative as gellant, but not for the one gelled with fumed silica. Thus from this experiment no correlation with shear viscosity could be derived for gels, which can be described as viscoelastic fluids.

A test campaign was conducted to understand the mechanisms leading to the formation of threads. Different kinds of non-Newtonian fluids were sprayed and their rheology was characterized. It was found that thread formation is strongly influenced by the non-linear elasticity of certain fluids. Such property could be characterized through elongational viscosity measurements (for gels) or by determining the relaxation time (for dilute solutions). The mechanism leading to the formation of droplets or threads in an impinging jet injector has been described using a two-step model. In the first step the liquid sheet breaks up into transversal ligaments. The second step differs for liquids with low and high elasticity. If the elasticity is low, the ligaments break up into droplets. Such disintegration is caused by capillary instability. It has been shown that the growth in instability is arrested if the elasticity of the fluid is high enough to prevent the disruption of the transversal ligaments due to capillary instability.

**Flash and Atomization of ADN-Based Propellants**

Flashing takes place during atomization when vapor bubbles are suddenly formed inside the liquid phase. The bubbles undergo a rapid expansion altering the general structure of the spray and reducing the final size of the droplets of propellants. This occurs typically during the ignition phase of orbital thrusters when a propellant is injected into a combustion chamber under near-vacuum conditions. The studies available in literature on flashing are based on pure substances, whereas ADN-based propellants, however, are salt solutions in a mixture of solvents. Ongoing study compares the flashing of water and solutions of water and urea. Urea salt was chosen as a non-explosive ADN substitute. The objectives are to...
determine how the solute influences the flashing behavior of the liquid solvent, and whether during flashing a segregation or crystallization of the solute takes place.

Figure 1.36: Shadowgraph image of the atomization under near-vacuum conditions.

The tests with urea water solutions of different concentrations have shown that segregation is an issue. For some injector geometries crystallization occurs even at low feed pressures and in a subcooled state (<3 bar; T=30°C). Additionally, the crystallized salt was accumulated upstream. If it accumulates in crucial parts like the flow control valve, this could lead to a failure of the valve.

The atomization of ADN-based propellants with three different injectors was studied. Two injectors were of micro-showerhead type, designed and manufactured by Airbus Safran Launchers. A commercial swirl injector was tested as well. In combination three fluids were tested: LMP-103S, FLP-106 and water. The spray tests were conducted under near-vacuum conditions. A schematic of the experimental set-up is shown in Figure 1.37. The pressure loss for each injector as function of the mass flow rate of the fluid was determined. Based on these data, the discharge coefficients for each injector were calculated. The spray patterns were characterized using a high speed shadowgraph technique which allowed the determination of the spray angle and of the breakup length.

Figure 1.37: Schematic drawing of the experimental set-up used to test different injectors.

1.4 Start Transients and Ignition

The start-up transient of rocket engines is a critical phase in the operation of a rocket engine, whether in flight or on the ground (e.g. in test benches). This is especially true for upper stage engines which are ignited at high altitude conditions. The Aestus anomaly of Ariane 5G flight 142 demonstrated the challenges met when trying to master the ignition transient. As in the case of the start-up, also shutdown, throttling, and purging are affected by the dynamic behavior of the fluids, the engine components and their interaction. For cryogenic propellants particular attention has to be paid to their behavior under thermodynamic non-equilibrium and multiphase conditions. The dynamic processes during the transients of liquid rocket engines may lead to undesired pressure peaks and pressure oscillations. This peak pressures can be dimensioning for the structural design of the supply system, thus a reliable prediction process is required. Prediction ability of transient flow behavior also supports test operation in definition of the sequences at test benches. A specific topic is the ignition transient inside the combustion chamber. The flame evolution and stabilization of classical torch igniters as well as new ignition technologies like laser ignition are tested.

Transient Flows

Basic transient flow behavior tests are performed at a dedicated test bench, the M3.5 facility. Testing is carried out to investigate the behavior of fluids after the opening or closing of valves. These investigations create the basis for better understanding fluid flow conditions prior to ignition and therefore the ignition process itself. The data sets are used to validate models for transient flow behavior prediction, in
particular in connection with the ECOSIM software with ESPSS library.

The framework of the DLR Verbundvorhaben “Forschungsverbund Oberstufe” (FOS – Upper Stage Research Association) tests at M3.5 are set down in a group effort with Airbus DS in order to increase the understanding of the launcher upper stage system and to maximise the significance of the tests for the real systems.

Water tests conducted at the M3.5 show phenomena which are observed in connection with storable propellants as used in reaction control system (RCS) engines and orbital manoeuvring systems (OMS) of launchers and satellites. A dedicated test campaign has been carried out successfully to reproduce the start-up transient of upper stage and satellite engines. High-speed flow visualisation is a powerful means to gain valuable information on the complex flow evolution in transient conditions (Figure 1.38). Efforts are focusing on the effect of the gas desorption. In tests the dissolved pressurising gas, GHe or GN2, is released as the pressure drops, thus creating a highly non-homogeneous, two-phase flow pattern. The pressure wave characteristics, such as pressure peak and frequency, are significantly different compared to tests with deaerated and therefore the desorption process needs to be properly modelled.

**EcosimPro**

The commercially available EcosimPro software together with the ESPSS library is used for the simulation of transient flow behavior. Experimental data from the M3.5 test bench is used to assess the accuracy of the numerical modules for a range of different two-phase flow conditions for both cryogenic and non-cryogenic fluids. This data is also used to improve these models if necessary. For example, the test data obtained at M3.5, has been used to validate new unsteady friction models implemented in the code, as well as a proper sub-model for the aforementioned gas desorption.

The improvements to EcosimPro developed by DLR are passed on to the software producer so that they can be made accessible to all EcosimPro users (NB: the software distribution is restricted to ESA member states). Industrial researchers and developers using EcosimPro in the development of satellite or launcher fluid systems therefore also directly benefit as a result of this process.

The experience gained in modelling an applied research test-bench such as M3.5 is passed on to test facility P8. A numerical model of the propellant supply system of both LOX and LH2 (Figure 1.39) has been developed and is under way to be benchmarked using data from DLR test campaigns currently performed at P8. The validated model will then help in the preparation of test sequences to ensure a safe and reliable operation of the test facility and the test specimens.

**Laser Ignition**

The Institute of Space Propulsion has been working within the field of laser ignition technology for more than a decade. The interest in igniter technology has increased because there has been a growth in the demand for new and improved re-ignition systems as, for example, for the upper stage Vinci engine. The search is on for ignition technology for future space propulsion systems with non-toxic, non-hypergolic
propellants. Weight reduction and redundancy aspects have led to an increase in the number of studies in alternative igniter technologies like laser ignition.

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) can offer numerous advantages:

- Ignition takes place at a pre-determined location within a combustion chamber.
- There is no need for ignition system propellant valves.
- A precise firing sequence can be defined.
- Simultaneous ignition of multiple rocket chambers is possible.

Laser ignition is applicable in the case of Reaction Control Systems (RCS), large-scale rocket combustion chambers and future engine applications, such as the rocket based combined cycle (RBCC).

In close cooperation with Airbus Safran Launchers and CTR AG DLR studied the ignition process under ambient and vacuum conditions using laser ignition within the ESA TRP projects “Cryogenic RCS Thruster Technology - Laser Ignition” and “Laser ignition technology”. More than 500 ignition tests for in-space conditions were carried out with LOX/H₂ and LOX/CH₄. A windowed, contoured, breadboard thruster (see Figure 1.40) operated at the M3.1 test bench allows laser ignition to be applied under in-space conditions including the use of flashing propellants and various ignition sequences (see Figure 1.41). Simultaneous high-speed Schlieren and image/intensified combustion diagnostics contribute to a more precise understanding of the injection, ignition, flame evolution, anchoring and stabilization processes and provide valuable data sets for the validation of numerical simulations and code development (chapter 1.10).

Based on the test results at the M3.1, a test campaign at the P8 test facility has been conducted with more than 1300 laser ignition tests of a multi-injector, cryogenic, experimental rocket combustor. The feasibility of multiple re-ignition by a laser igniter for LOX/H₂ and LOX/CH₄ for high thrust engines under ambient conditions was demonstrated using test sequences featuring up to 60 ignition cycles at 30-s intervals (see Figure 1.42). Ignition for propellant temperatures of \( T_{\text{OX}} = 10\text{ - }281 \text{ K} \) and \( T_{\text{H₂}} = 122\text{ - }282 \text{ K} \), or \( T_{\text{CH₄}} = 279\text{ - }290 \text{ K} \), was proven to be reliable. Optimal positioning of the point of ignition within the shear layer of a coaxial injector jet was also verified with a fiber optical sensor developed in-house for investigating flame dynamics in combustors. By combining the test results with the experience gained of the fundamental mechanisms achieved at the M3.1, an in-depth understanding of the scalability of the laser ignition technology is possible. Furthermore, the robustness of the laser ignition system and its applicability to cryogenic rocket engines were demonstrated, even for CH₄ configurations.

**Ignition of ADN-based Propellants**

Thermal igniters are attractive for ADN thrusters as they allow an instantly ignition and are more suitable for engines of 100 - 500 N class compared to the currently used preheated catalyst igniters. The two thermal ignition methods under investigation are laser and torch ignition.
Laser ignition was tested by suspending a droplet in an acoustic levitator as can be seen in Figure 1.43. The pulsed laser was focused to generate a plasma inside the droplet. The ignition tests were conducted with the baseline propellants LMP-103S and FLP-106 with the water content being varied.

The average droplet diameter during the tests was around 1 mm. This diameter is extremely large compared to the droplet diameter formed by a typical injector. This may have a major impact on the ignitability of the drops. Tests with smaller droplets were attempted. But, reducing the size induced a faster evaporation on the volatile components in the propellants, so that the composition of the droplet changed considerably before the test could be carried out. The tests with the 1 mm droplets showed that the laser spark disintegrated the droplet into a spray. After the laser pulse the droplet emitted a bright light. In some cases the emission of light took place for almost 100 µs. It was assumed that such a long time period cannot be solely due to plasma emission that should be completed after 10 - 20 µs, and a combustion was initiated or at least a propellant decomposition has started.

Figure 1.44 shows a set-up that was built to test H2/O2 torch ignition. The torch igniter delivered around 20 kW of thermal power. A commercial swirl injector was used to atomize the propellant. Preliminary tests showed that ADN-based propellants are difficult to be ignited thermally. Ignition is achieved only after propellant vaporization. Up to now vaporization was only achieved during injection of the propellant in short pulses into the chamber or by feeding additional oxygen into it.
quite simple, reliable and cheap method to ignite a propellant. Thirdly, the energy source for combustion initiation is a high temperature glow plug. Ignition of the propellant mixture via glow plug also has the advantage that it is a very cheap, reliable and simple ignition system. To raise the TRL level of the use of this propellant mixture the first challenge that has to be met is the avoidance of flashback during the ignition, steady state or shut down process of the combustor.

Figure 1.46: High-speed image of N₂O/C₂H₄ ignition

A gaseous N₂O/C₂H₄ mix is ignited in another test chamber under different static pressures. Here, the flame propagation and the combustion initiation conditions can be studied in detail. The geometrical characteristics of the test chamber are similar to the ones foreseen for the hot run tests. The test chamber can be filled completely with a gaseous propellant mixture whereas flashback arresting elements can separate into two volumes.

Figure 1.47: Ignition and flashback arrestor test chamber

Experiments are conducted both with and without elements preventing flashback. The tests without arresting elements are used as reference cases to analyse the general behavior of the reaction front, for example to derive the flame propagation speed. As flashback arrestors, elements made of different porous materials with small orifices are tested. Safe and reliable operating conditions (e.g. ignition pressure, mixture ratio, etc.) for application of the various elements are derived. Via variation of the ignition pressure the resulting flame speed, pressure peaks and average temperatures can be investigated.

The ignition chamber is equipped with pressure transducers and thermocouples. The implementation of a transparent window allows high-speed imaging. A high-speed image recorded during the ignition and flashback experiments can be seen in Figure 1.46. On the left side the spark plug used for ignition is visible. On the right side the circular fitting for the flashback arresting elements can be seen.

Transients in a Hybrid Rocket Engine

As previously described in chapter 1.2, optical investigations in a 2D slab burner have been performed as part of the research on hybrid rocket engines. The combustion phenomena of different paraffin-based fuels in combination with gaseous oxygen have been investigated. High-speed images of combustion tests were recorded and a spatial and temporal analysis of the main structures of the flame was performed. In particular the analysis was applied separately to data samples from the ignition, steady state and extinction. As during transients the flow conditions change rapidly the analysis was applied only to a short time period of 0.1 seconds. Figure 1.48 shows the contour plots of the spatial coefficients of the first POD mode (chapter 1.5) during ignition, steady-state and extinction. The color map in these plots represents the intensity of the flame luminosity and therefore it is non-dimensional.
In comparison to steady-state, the transient combustion shows a broader range of frequencies. Distinct wavelengths are not found during ignition. This might be because they are still smaller than the resolution of the camera in this phase of combustion. In Figure 1.48 it can be seen that the flame front and boundary layer are closer to the surface during ignition. The ignition event also shows brighter regions in the main region of the diffusion flame, which refer to more transient conditions and fluctuations in the flow field. This was to be expected since the ignition event is highly transient, as could also be seen in the image data. Shorter waves and droplet entrainment are visible during this phase. As the combustion is not at its peak value, the light emission is lower and therefore more details can be seen. The steady-state contour plot shows the typical boundary layer profile very well and with lower fluctuations outside of the region of the main flame. The extinction is covered again by a wider region of higher intensity corresponding to the rapidly changing conditions and blow-out of the flame during this process.

### 1.5 Combustion and Stability

Combustion instability is still a frightening phenomenon for development engineers despite the development of analytical and numerical design tools and decades of acquired empirical knowledge. The effects of combustion instabilities are well known to the European launcher community: episodes of combustion instability in the storable propellant engines Viking and Aestus as well as in the HM7B cryogenic upper stage have resulted in being unable to reach the target orbit or even in the loss of the mission. Unwanted, spontaneous combustion instability in a research rocket combustor can also complicate the data analysis and hinder the achievement of research objectives.

The ongoing need for better understanding combustion instabilities is the motivation to carry out further fundamental research in the subject at the Institute of Space Propulsion. The focus is on experimental work with the key objective of determining the mechanisms by which energy from the combustion process is transferred into the acoustic field of an excited resonance mode of the combustion chamber. Other areas addressed are the performance of passive damping devices and CFD modelling of flame-acoustic interaction.

DLR works on the subject of combustion instabilities under the terms of an MoU together with German and French partners from industry, research institutions and agencies (ASL, CentralSupélec Paris, CERFACS, CNES, CNRS, CORIA, IMFT, ONERA, Technical University of Munich). The Rocket Engine Stability Initiative (REST) meets regularly and holds scientific workshops and workshops on numerical modelling. DLR also cooperates with German Universities in a special research field, Transregio 40 (SFB TRR 40) project, as well as with other international partners including JAXA (Japan) and Victoria University (Canada).

**Interaction of Acoustics and Combustion; Combustor H (BKH)**

Combustor H (BKH) was designed to be operated at the P8 and is specially configured for the visualisation of rocket flame response to forced acoustic perturbations. The goal is to capture flame response phenomena on a physical scale and under conditions...
relevant to those experienced in connection with actual rocket engines.

The configuration of BKH, shown conceptually in Figure 1.49 features a rectangular cross-section and five shear coaxial injection elements clustered centrally. Operating conditions with LOX/H₂, such as injection temperatures, mass flow rates, and chamber pressure, are aimed at being representative of those as in upper stage cryogenic engines. A siren is incorporated in the upper wall for acoustic forcing. Forcing at the frequency of the first transverse mode of the combustion chamber, around 4200 Hz, subjects the five flames to high amplitude, transverse acoustic velocity perturbations.

Figure 1.49: Conceptual illustration of BKH

Multiple dynamic pressure sensors mounted in the chamber walls allow the acoustic response of the combustor to be characterised according to different operating conditions. Methods for measuring acoustic damping with siren excitation under noisy, high-power combustion conditions have been advanced and quantitative values have been published. The dependence of damping on injection parameters and operating conditions was examined, and injection velocity ratio, for example, was found to influence measured damping rates, as can be seen in Figure 1.50.

Figure 1.50: Hot-fire damping rates in BKH as a function of injection velocity ratio

Optical access windows allow the flame response to acoustics to be observed in the near-injection region. Two high-speed cameras record images synchronously at rates of up to 30,000 frames per second. The first camera is for backlit shadowgraph imaging to resolve the dense oxygen jets. An example instantaneous shadowgraph image is shown in the upper part of Figure 1.51. The second camera collects OH* emission from the flame via a dichroic mirror, filter, and intensifier. An example image is shown in the lower part of Figure 1.51.

Shadowgraph imaging from such experiments has revealed the significant response of the LOX core to transverse instability. The intact core shortens in length due to accelerated breakup and mixing driven by the transverse acoustic gas oscillations. Simultaneous OH* chemiluminescence imaging showed a corresponding change in the extent, emission intensity, and dynamics of the flame. The two sets of time-averaged shadowgraph and OH* images in Figure 1.52 illustrate this effect. Understanding this flame response in detail is important for predicting combustion instabilities.

Figure 1.51: Example instantaneous shadowgraph and OH* images from BKH.

Figure 1.52: Time-averaged shadowgraph (upper row) and OH* (lower row) images without (left) and with transverse acoustic forcing (right).
Using the shadowgraph imaging the trend in decreasing core length in relation to acoustic amplitude could be established. Core length was measured from a series of shadowgraph images taken during varying acoustic forcing amplitude. An example data set from a single test run is shown in Figure 1.53.

Figure 1.53: LOX core length measurements under varying acoustic amplitude

**Injection Coupled Instability; Combustor D (BKD)**

The research Combustor D (BKD) is a multi-purpose sub-scale rocket combustor operated with LOX/H₂ at the P8. It exhibits spontaneous acoustic resonance for some operating conditions and it is therefore used for the investigation of combustion instabilities.

As can be seen in Figure 1.54, BKD resembles a conventional thrust chamber configuration, with a cylindrical combustion chamber and multi-element injector head. The chamber diameter is 80 mm and the operating conditions are representative of modern LOX/H₂ flight engines.

A special measurement ring is installed between the injector head and the cylindrical segment. The ring, depicted in Figure 1.55, is equipped with eight dynamic pressure sensors to record the acoustic field, and 10 fibre-optical probes to collect point measurements of dynamic flame radiation. The probes were specially developed by the DLR combustion instabilities group to withstand the harsh conditions in real rocket engines. The measurement ring has proven to be a successful and flexible method of obtaining reliable, detailed measurements from the hostile environment of a combustion chamber.

Figure 1.54: Illustration of BKD

Figure 1.55: Measurement ring in BKD (left) and a photograph of an optical probe (right).

Figure 1.56 shows a typical test sequence of BKD, comprising nine load points defined by $p_{cc}$ and ROF. Stable and unstable operating conditions can be identified in the dynamic pressure ($p'$) signal and spectrogram in the upper two sections. The strongest instabilities of the first tangential (1T) resonance mode were found for the 80 bar, ROF 6 load point between around 18 and 24 s. Increased oscillation amplitude is evident in the $p'$ signal and the spectrogram shows strong activity of the 1T mode at 10 kHz.
The analysis of the experimental data was sufficient to explain the conditions under which BKD becomes unstable. The fluctuations of OH* emission intensity from the optical probes show dominant frequency rates corresponding to LOX post acoustic resonance frequencies, independent of chamber acoustics. Instability of the 1T mode occurs when one of the LOX post resonance frequencies coincides with the chamber 1T frequency. This mechanism does not correspond to the alleged response of LOX posts to chamber acoustics reported in the past and referred to in literature. More detail about the coupling is being revealed by analysing the phase of optical signals compared to the dynamic acoustic field, reconstructed from the dynamic pressure signals using an in-house program. Thus, optical access has proved to be indispensable in understanding the mechanism of instability dominant in BKD.

**CFD Modelling**

Data from both the BKH and BKD experiments were formulated into test cases for the REST community as part of a modelling workshop. The workshop was very successful, showcasing many different modelling approaches and resulting in several follow-on team efforts.

DLR also models these combustion instability experiments using the DLR TAU code flow solver with the support of developers at the DLR Institute of Aerodynamics and Flow Technology. The goal of these modelling efforts is to investigate flame-acoustic interaction with higher imaging quality and complete access to all parts within the flame. By simulating the BKH configuration and comparing it with experimental results, the ability of the model to capture high amplitude acoustics and flame response phenomena is being examined. A validated model could in future be used to predict the stability of real engine configurations. The combination of TAU flow field results and a three-dimensional finite element acoustic solver has already been demonstrated to improve the accuracy of the modal analysis of BKH (Figure 1.57).

**Optical Investigations on Hybrid Rocket Engines Combustion**

As mentioned in chapter 1.2 liquefying hybrid rocket fuels are characterized by the entrainment phenomenon which is able to increase the regression rate of this kind of fuels. In order to better understand this process a deeper insight into the combustion phenomena of liquefying fuels is needed. For this reason combustion tests of paraffin-based fuels in combination with gaseous oxygen have been performed in a 2D slab burner with windows on two sides. Different fuel viscosities and slab configurations have been tested in combination with different oxidizer mass flows, in order to understand the influence of these parameters on the liquid layer instability mechanism. High-speed images have been recorded to investigate the flame behavior (see Figure 1.58).
In order to better evaluate these flow phenomena, characteristic frequencies and wavelengths of the main structures of the flow field and the combustion flame appearing in the image data have to be found. In the course of this research a spatial and temporal analysis of these structures is carried out by using two different techniques applied within an automated video evaluation routine. First of all, the Proper Orthogonal Decomposition (POD) technique is used. Its results deliver linearly uncorrelated variables which are the principal components of the flow field. Using this method the main structures of the flow field and the combustion flame appearing in the video data can be recognized. Secondly, the Independent Component Analysis (ICA) technique is applied to the same data. It is able to search for statistically independent, or as independent as possible, structures hidden in the data. It increases the independence to higher statistical orders with respect to POD. The basic functions found with the ICA are expected to describe the essential structure of the data and to resemble some physical processes involved in the combustion. With both methods it is possible to compute spatial and temporal coefficients which can later be analyzed by applying a Power Spectral Density (PSD) in order to obtain the excited frequencies and wavelengths during the combustion.

Before applying the two decomposition methods a pre-processing of the images has to be made. The steps are summarized in Figure 1.60.

In a first step the images are exported and cropped. Usually filters are added to adjust brightness and contrast. There also exists lateral burning at the sides of the fuel, so the bottom of the fuel is also cropped just up to the solid-liquid interface to reduce noise and errors. The angled front and the rear end, where further vortices are created, are not included in the frames.
In a second step, the images are converted from true-color RGB to binary data images, based on a luminance threshold.

The third step removes a part of the background noise of the images. Mainly small light spots are removed in this process which are supposed to be burning paraffin droplets. Lots of them are appearing during ignition process as the overall illumination from the flame is not too bright.

Fourth, an edge detection algorithm is applied. It has to be noted that image data is a line of sight measurement. Thus, the data in the POD analysis represents an integrated measurement over the complete fuel slab width. This has to be taken into account when analyzing this data.

Finally, the data is tailored by auto-scaling with mean centering and standardization.

This process is done for each frame and a so-called Snapshot Matrix is created. This matrix will then be decomposed with the two techniques described previously.

Fuel Composition and Configuration Analysis

During the test campaign different configurations and fuel compositions were tested. By analyzing the PSD results of POD and ICA it is possible to obtain the main frequencies and wavelengths for each of them. The analysis was carried out for 1 second (10,000 frames) during the steady-state. Frequency and wavelength peaks were compared for each type of fuel formulations and configurations.

As regards the fuel formulations a dependency of the main frequencies and wavelengths from the fuel viscosity was found. The frequency peaks are all in the low and/or medium frequency range (<600 Hz) and their values decrease as the viscosity increases. The longitudinal wavelengths show peaks in the range 0.2 – 2 cm. This is in the range of the critical and most amplified waves predicted by the Kelvin-Helmholtz instability theory. Moreover, by increasing the fuel viscosity, the frequency values decrease and the longitudinal wavelengths increase.

As regards the fuel configurations three different slab configurations were tested. In the configuration with the 30° forward-facing ramp a broader range of frequencies are excited for every fuel composition with respect to the configuration with the 5° ramp. This is thought to be related to the vortex shedding which is produced by the front step. In the configuration with the forward-facing step, a big zone of flow separation and recirculation can be seen in the images directly after the step (see Figure 1.58). In this case different frequencies are excited which are connected to the vortices released by the separation zone and to the flapping motion of the shear layer in the separation region.

Moreover, it was observed that by increasing the oxidizer mass flow the values of the excited frequencies become higher while those of the excited longitudinal wavelengths become smaller. No longitudinal waves are excited for very low mass flows (<30 g/s).

1.6 Heat Transfer and Cooling

Optimization of heat transfer management is a key issue in designing a rocket combustion chamber. Heat transport processes are therefore of ongoing interest at the DLR Institute of Space Propulsion. The future generation of rocket engines should comply with the requirements of high efficiency, reliability, and especially with respect to application in re-usable vehicles with increased life time. To fulfill these requirements the engine performance as well as the load capacity of the engine has to be improved.

Efficiency, performance and specific impulse of rocket engines can be improved when operated at higher combustion chamber pressures. However, by increasing pressure the thermal loads to the com-
bustor also increase. Reliable operation of combustion chambers with such high thermal loads is achieved only by implementing highly efficient cooling systems that use a combination of different cooling methods. The new design concept focuses on well-established conventional regenerative cooling techniques as well as, to an increasing degree, on film cooling and alternative cooling systems. Because most rocket engines components already require attributes from material close to their limits of capability significant improvement in cooling efficiency and of material characteristics are the criteria which decide on how space transport systems can be enhanced.

For an optimum cooling design a precise knowledge of heat transfer process in rocket engines is mandatory. Despite extended experience there still exists the need to gain quantitative data on thermal loads under representative conditions with both hot gas and coolant wall sides for the validation of design tools. The importance of this data is confirmed by the fact that life cycle prediction of rocket engines depends to a large extent on the accuracy of wall temperature prediction, i.e. an error of 40 K leads to a 50% reduction in the lifecycle.

In its research strategy on heat transfer processes the DLR Institute of Space Propulsion combines both experimental studies with numerical modelling. Test set-ups used to generate high fidelity data for code validation range from experiments on a laboratory scale up to test runs in high pressure research combustors at the P8 (see Figure 1.61).

![Figure 1.61: Different configurations of investigated cooling channels.](image1)

Heat Transfer in Cooling Channels with Cooling Fluids at Supercritical Pressure

A significant part of the research activities focuses on the influence of subcritical, transcritical and supercritical conditions in the heat transfer in cooling channels. For this reason a new test facility, M51.3, has been designed and built (Figure 1.62). At this test position the effects of heat transfer in electrically heated tubes can be studied. These experiments supply data for the DLR ProTAU project which will contribute to a better understanding of the heat transport processes at steady state as well as under transient conditions.

![Figure 1.62: M51.3 test facility for investigation heat transfer at sub-, trans-, and supercritical conditions (down) and numerical simulation of supercritical flow in cooling channel (top).](image2)

Heat Transfer in Cooling Channels with High Aspect Ratio

A new test campaign at P8 with combustion chamber D is being prepared to determine the effect of cooling channel aspect ratio on the heat flux into the chamber wall. By varying the cooling channel mass flow the wall surface temperature will be adjusted from below condensation temperature up to about 700 K. In preparation for this campaign detailed numerical simulations were performed using CFX. Para-hydrogen and methane are simulated as real gases with 50 K (hydrogen) and at a (methane) temperature of 120 K at the cooling channel inlet (Figure 1.63).

![Figure 1.63: Numerical simulation of supercritical flow in cooling channel.](image3)
In parallel data reduction tools to extract heat transfer data from the experiments were improved and tested. The 3D inverse method can be used to determine the complete temperature field and the corresponding boundary conditions (heat transfer coefficient on hot gas and cooling wall side) based on discrete temperature measurements in the wall structure. The 3D simulation of a complete cooling channel takes into account the axial heat conduction. The increase in improvement in the results from the 3D as opposed to the 2D simulations is remarkable (Figure 1.64).

Film Cooling

2D Thermal load distribution in combustion chamber E (BKE):

Examining how thermal and chemical loads affect the chamber wall near the injector is of significant importance because the chemical properties of LOX and radicals have an impact. This area is characterized by the effects of the progress of propellant atomization and mixing and also by the severe temperature conditions, concentration and velocity inhomogeneities between the streamlines of individual injectors. Figure 1.65 shows that the form and intensity of the load distribution on the chamber wall obviously depends on the position and arrangement of the injector elements in the outer row.

Due to the extremely complicated flow phenomena (high pressure, extreme variation of flow properties, steep temperature gradients, reactive turbulent flow etc.) the ability to properly predict with CFD methods in the near injector region is limited. Detailed information on heat load distribution can only be gained by experiments. Figure 1.66 shows an example of the measured circumferential distribution of the heat flux and surface temperature at various distances from the injector head in BKE. The values are derived from measurements taken according to the inverse method. Tests were repeated and involved altering the angular increment by rotating the measurement segment. The tests covered several measurement points for each cluster of thermocouples at various angular positions. On the basis of these measurements the two-dimensional distribution of the thermal load inhomogeneity was reconstructed. The deviation of the measured heat flux value from the integral average value at corresponded axial position

\[ \Delta q(\alpha, x) = \bar{q}(\alpha, x) - \left( \frac{1}{18^\circ} \right) \int_{18^\circ}^{18^\circ} q(\alpha, x) \, d\alpha \]

is shown in Figure 1.66.
Figure 1.66: Distribution of the heat flux density at different angles to injector element axis at $p_{CC} = 11.1$ MPa, ROF=6.0

Film Cooling in Combustor BKM:

The analysis of the results of the BKE film cooling experiments has shown that the cooling film efficiency is affected by its interaction with the injected propellant jets and the flow field near the injection plane. Optical visualization techniques have to be applied to explain the effects of this interaction in more detail. BKE has no optical access so a new research combustor M (BKM) has been designed to enable film cooling to be examined under representative conditions. BKM has optical access and will allow the application of visualization techniques. It is equipped with instrumentation particularly suited to measuring in detail the heat transfer to the hot gas wall. DLR has worked closely with JAXA according to guidelines defined in the DLR/JAXA Research Agreement on the justification of the BKM design. Figure 1.67 shows JAXA’s numerical simulation of the predicted reactive flow field in the BKM combustion chamber.

Film Cooling in the Nozzle Extension:

The impact of the thermal loads on the nozzle extension is relatively low as compared to the effects on the combustion chamber. However, in the past thermal loads in actual nozzle designs have appeared to be a critical factor. Therefore research has been carried out into heat transport processes using the BKE thrust chamber model which reproduces Vulcain 2 nozzle geometry on a scale of 1:8.

Figure 1.67: numerical simulation of combustion chamber model "M". Mass fraction of $\text{H}_2\text{O}$ (Results of the cooperation JAXA and DLR)

Figure 1.68: heat loads in regeneratively cooled section of the BKE thrust chamber nozzle.
Experiments carried out in the BKE increase the current database on film cooling in liquid propellant combustion chambers and thus allow for a better understanding of heat transfer processes under real conditions. Testing of the film cooling efficiency in the supersonic part of a nozzle extension also revealed some basic information on the effect of flow separation during engine start-up on thermal loads. It is possible to evaluate the prediction ability of the design tools currently used at DLR as well as more sophisticated CFD models (Figure 1.69) as a result of the data collected.

Figure 1.69: Numerical simulation of the film cooled nozzle flow in BKE.

Investigation of Heat Flux During Combustion Tests with HyNOx

Along with the high specific impulse of the propellant mixture, combustion temperatures are high. During the reaction process, inside the combustion chamber more than 3000 K can be reached.

Figure 1.70: Heat flux vs. test duration, torch ignition

Those high temperatures require adequate cooling of the chamber walls. To develop and use such a cooling system detailed knowledge about the heat flux into the wall material needs to be generated. By equipping the combustion chamber with several thermocouples, the temperature history during the combustion tests is derived and analysed. In cooperation with TU Munich their specialized tools were used to derive the corresponding heat fluxes. By knowing the heat flux the operating range (mass flow, pressure, etc.) of the combustor can be defined and the results can be used for designing future thrusters. A selection of the resulting heat fluxes by variation of the mass flow is shown in Figure 1.70.

1.7 Lifetime Assessment

Assessment of the lifetime is a key discipline in the design of rocket combustion chamber structures exposed to high thermal loads and is especially true regarding the design of re-usable engines. The cyclic thermal and structural loading of the inner liners of combustion chamber wall structures results in cyclic plastic strains of about 2% for core stage engines like Vulcain 2. In order to obtain accurate lifetime prediction, the following effects have to be taken into consideration on site:

- Temperature dependency of all of the elastoviscoplastic material parameters.
- Combination of kinematic hardening with cyclic isotropic softening (for low and moderate temperatures also cyclic isotropic hardening for the first few cycles).
- Short term viscoplastic effects such as a stiffening of the material for high strain rates.
- Long term viscoplastic effects such as e.g. stress relaxation in a strain controlled structure.
- Thermal ageing: reduction of the yield stress during long periods of being subjected to high temperature due to grain growth inside the chamber wall material.
- Cyclic reduction of the modulus of elasticity due to internal crack initiation – this Finite Elements Integrated Damage Parameter approach also replaces the conventional Post Processing Fatigue Life method (based on the Coffin-Manson diagram with or without additionally taking ratchetting effects into account).
- Directional dependency of the modulus of elasticity if damage has already been caused even where materials are used which are initially isotropic, i.e. the so called crack-closure effect results in a higher modulus of elasticity in the
compressive part as compared to the tensile part of the deformation.

All of the above mentioned effects are included in the actual structural Finite Element analysis software used by the Institute of Space Propulsion called ANSYS, which is a Finite Element package available commercially with programmable features and upgraded by a series of in-house elementary level subroutines.

```
\begin{align*}
\text{Modelling of the Hydrogen Embrittlement of Metallic Materials}

\text{Hydrogen embrittlement is a material degradation which leads to a softening in plastic behavior and to a decrease in the ultimate strain level of the material (ductility loss). As a first step in modelling hydrogen embrittlement high cycle fatigue (HCF) analysis is used to look into stationary embrittlement. For cyclic plastic deformation LCF behavior can usually be observed. Elastic behavior of the material can be assumed for HFC analyses. Since the modulus of elasticity is usually not influenced by hydrogen within the material, hydrogen embrittlement can then be taken into account by a post processing method. According to this assumption the hydrogen concentration in the metal lattice } C_L \text{ can be determined by applying the following equation:}
\end{align*}
```

\[ C_L = k_0 \exp \left( \frac{\sigma F - \Delta H}{RT} \right) P_{H_2} \]

with:
\begin{itemize}
  \item \( k_0 \) temperature independent term of the Sievert’s constant
  \item \( s_h \) hydrostatic stress \( s_h = s_{hk} / 3 \)
  \item \( V_H \) partial molar volume of H₂ in solution
  \item \( \Delta H \) molar lattice enthalpy
  \item \( R \) universal gas constant
  \item \( T \) temperature
  \item \( p_{H_2} \) pressure of external gaseous hydrogen
\end{itemize}

Once the hydrogen concentration in the metal lattice \( C_L \) is determined, its influence on the HCF behavior of wall structures is taken into account by the “Wöhler plane” approach proposed by the DLR-Institute of Space Propulsion: a Wöhler line extended by the hydrogen concentration as a third dimension.

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**Figure 1.71:** 3D (mechanism symbol) visualization of the Finite Element integrated structural analysis method available at the Institute of Space Propulsion.

**Material Parameter Determination**

All of the material parameters needed for the numerical analysis have to be least squares based on the results of tests with uni-axial material samples. In Figure 1.72, the good coincidence of the numerically obtained isotropic softening with least squares fitted parameters with the experimentally determined isotropic softening (for temperatures lower than 900 K and also cyclic hardening in the first few cycles) is demonstrated by plotting the drag stress \( R \) in dependency on the accumulated plastic strain.

**Figure 1.72:** Numerically obtained and experimentally observed drag stress \( R \) of the DLR TMF panel material taking into account the accumulated plastic strain for four different temperatures.
Validation of Numerical Analyses

Materials used in the production of combustion chamber wall structures have to withstand extreme conditions such as:

- temperatures of 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.

Such aspects often exceed the scope of standard numerical methods used for a structural and fatigue life analysis of the chamber wall structure. Therefore, validating the numerical data to support the design of new (full scale) hot gas wall structures is essential.

Data collected from previously tested models, sub scale or full scale combustion chambers can be used for validation.

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<td>deformation</td>
<td>perthometer or microscope</td>
</tr>
<tr>
<td>fatigue life analysis of the wall structure</td>
<td>counting the number of loading cycles until the structure fails</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Validation possibilities for numerical analyses of thermally loaded wall structures.

Although the parameters shown in Table 2 would seem to deliver considerable validation data, some limitations exist in the case of combustion chambers as regards hot run tests:

- It is only possible to measure the temperature point by point by using thermocouples.
- Only the following deformation can be measured and taken into account:
  - Out-of-plane deformation;
  - Measurements taken before and/or after - but not during - the hot run.

In order to overcome the above mentioned measurement restrictions, the TMF test facility is used at the Institute of Space Propulsion – allowing for tests of small combustion chamber wall cut-outs (so called TMF panels) by replacing the hot gas loading of the chamber with a laser radiation loading. The unique
measurement capabilities of this test facility and its validation capability are listed in Table 3.

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

Table 3: Unique measurement capabilities and validation possibilities of TMF tests (which are not possible for combustion chamber tests).

**Validation Test Specimen**

A sample made for validation purposes and used on the TMF test bench of the Institute of Space Propulsion is shown in Figure 1.75.

![Figure 1.75: Validation test specimen (TMF panel), its thermal loading (by a laser) and active cooling (by \( \text{N}_2 \)).](image)

This specimen represents a 5-channel cut-out of a much larger thermally loaded full scale structure with coolant inlet and outlet connections at both ends. The copper base alloy is covered by a thin coating in order to increase the absorption of the wavelength of the heating laser. Both the heat flux through the wall structure as well as its surface temperature can be regulated separately by varying the heating laser power and the \( \text{N}_2 \) mass flow rate through the cooling channels of the thermally loaded structure.

**Validation Results**

During testing the TMF laser is switched on and off until a failure occurs in one of the cooling channels of the TMF panel. This approach simulates a series of ignition and shut-down cycles (up to failure) of a combustion chamber. After the TMF test a cross section cut was made in the panel along where the failure occurred in order to visualize in 2D the deformation of the cooling channel structure. In Figure 1.76, the numerical analysis of the failure is compared to the real panel deformation. Obviously, the Finite Element analysis taking into account thermal ageing damage and the crack closure effect is able to predict both: the increase in thickness in the fin areas of the TMF panel as well as the crack position at the symmetry line of the cooling channel indicated by a damage value \( D \) of close to one. Also, the dog house effect observed during the experiment (i.e. bulging of the cooling channel wall towards the thermally loaded side of the TMF panel) can be reproduced to a certain extent in the numerical analysis.
Figure 1.76: Result of a Finite Element integrated damage parameter based analysis of a TMF panel compared to the experimentally observed middle cross section of the TMF panel.

1.8 Thrust Chamber Technology

Quantitative measurements of fluid mechanical and thermodynamic properties in reactive flows at rocket engine conditions require dedicated instrumentation and measurement techniques. For this reason research combustors are designed in such a way that they can reproduce the conditions of interest in a well-defined and controlled manner. They enable the implementation of specific sensors and optionally provide optical access to the reactive flow in the combustor. The modular design allows individual combustor components to be exchanged, for example the injectors and so increasing the variations in the test configuration and the number of different tests which can be carried out. The Department of Rocket Propulsion has key expertise in the area of combustion chamber technology and extensive design know-how. The following are research combustors in operation at the P8.

Research Combustion Chamber Model I (BKI)

Gas generators and pre-burners provided the parameters for designing and constructing the BKI research combustion chamber. The typical conditions which determine the design allow the following test objectives to be achieved successfully:

- Determining combustion efficiency.
- Assessing combustion stability and roughness.
- Identifying temperature stratification of the hot gas.

In addition to chamber pressure, mixture ratio and propellant inlet conditions, realistic operating conditions also include a representative combustion chamber shape which determines the flow field. Typical Mach numbers inside a pre-burner are considerably lower than in a main combustion chamber. The configuration presented here used a nozzle segment with an exchangeable throat.

Figure 1.77: DLR subscale combustion chamber BKI, schematic (up) and mounted at P8 (bottom).

The determination of the combustion efficiency was based on the JANNAF recommendations. For this reason the static pressure was determined on various axial locations inside the combustion chamber.

A chamber diameter of 80 mm was chosen which corresponds with the typical inner diameter of DLR subscale chambers. A direct comparison can thus be made of the operational behavior of different injector head configurations under varied injection conditions.
An important parameter for pre-burner applications is the stratification of the hot gas flow. The overall chamber mixture ratio determines the mean temperature of the combustion gases. If mixing however is not carried out perfectly this might cause high temperature streamlines to persist and they might reach as far as the first row of the turbine blades. To measure the thermal stratification several thermocouples have been applied inside the combustion chamber at multiple radial and angular positions. An additional measurement ring was inserted directly upstream of the nozzle segment. This measurement ring featured three beams made of Inconel which met in the chamber's centerline. The thermocouples were mounted at various locations on these beams. The application of thermocouples and the Inconel measurement ring was only possible due to the comparably low temperature of the combustion gases. The subscale combustion chamber has a modular design that allows the implementation of a variety of measuring devices. Figure 1.77 shows the combustion chamber assembly.

The length of the cylindrical chamber was 290 mm. The resulting characteristic chamber length is L*≈4.9 m and 11.1 m depending on the nozzle throat diameter. DLR achieved a European record for a subscale test chamber by creating a combustion chamber pressure of 330 bar.

**Research Combustion Chamber Model K (BKK)**

Additive layer manufacturing methods (ALM) are relatively new techniques which have shown a rapid rate of development in recent years. Vacuum Plasma Spraying (VPS), Laser Metal Deposition (LMD), Selective Electron Beam Melting and Powder-Bed Selective Laser Melting (SLM) are examples of such manufacturing processes. SLM uses a powder bed in which the components are formed layer by layer by fusing melted powder. Additive layer manufacturing enables the creation of 3D structures that cannot be manufactured by conventional production methods. SLM is of major interest for cooled structures because this technique allows the production of cooling channels with a relatively good surface finish and with a wide spectrum of design solutions to optimize cooling performance. As part of a concept study DLR’s Institute of Space Propulsion examined whether SLM is suitable for the production of rocket propulsion components.

The focus of the study was the development of basic technologies and design methods as well as the verification of design solutions for key components of an SLM combustion chamber. The activities included investigating the most important design aspects of combustion chambers, such as gas tightness, geometric accuracy, and surface roughness (Figure 1.79). The results of this preparatory work were used in the design of the combustion chamber from a heat-resistant nickel alloy.

SLM was used to produce the combustion chamber with cooling passages and throat as an integral part in one manufacturing process. The design of the cooling channels which helically encompass the cylindrical combustion chamber was chosen to optimize the cooling effect. The functionality of the SLM combustion chamber has been demonstrated in hot firing tests (Figure 1.81).
BKM was designed and constructed in order to achieve the following scientific objectives:

- Investigation of the interaction of combustion gases with the cooling film close to the faceplate.
- Elimination of wall influence and secondary flow effects on the injection flow.
- Investigation of the dynamic pressure impact on the film cooling layer.
- Simultaneous data recording with high accuracy of 2D wall heat fluxes, static pressures, and flow topology.
- Creation of a comprehensive data base for the verification and advancement of numerical tools.

To accomplish these objectives BKM has unique design, construction and assembly features. It combines a rectangular combustion chamber in conjunction with multi injectors. The faceplate is equipped with nine injector elements. The outer injector elements eliminate the effects of wall and secondary flow from the inner three injector elements. The focus of the tests is on these inner three injector elements together with the film cooling slots.

The purpose was to draw on the experience and the computational power of JAXA in the numerical simulation of rocket combustion chambers and to get detailed numerical data on the flow and the combustion process in BKM.
Optical access to the region near the faceplate is provided from three sides. These windows can be replaced by dummy panes equipped with thermocouples and dynamic pressure sensors to investigate heat load and dynamic pressure impact on the film cooling layer.

BKM is designed to operate at three relevant pressure levels including sub, near and supercritical conditions with respect to the critical pressure of oxygen and with mixture ratios of up to 6. The temperature of fuels, oxidizer and cooling fluids can be ambient and cryogenic. Possible oxidizer/fuel combinations are LOX/GH2, LOX/LH2, LOX/GCH4, LOX/LCH4). For film cooling GH2, GHe, LH2, GCH4, LCH4 can be used. Because of its specific injector head design, tracer particles can be added by way of any of the five film cooling slots independently of each other. Also the oxidizer supply of each injector element can be controlled separately. The injector head with several dispersion elements is so designed that fluids are uniformly distributed. This method was verified by means of CFD simulations.

In addition to the optical measurements system, static pressure sensors and thermocouples are mounted in a dummy water-cooled window. They can be used to supply a 2D profile of static pressure and wall heat fluxes along the length of the combustion chamber.

Transpiration Cooling (Scramjet)

Scramjets (supersonic combustion ramjets) are of interest for advanced reusable TSTO systems. The engines face high wall heat fluxes and thus high thermal loads on the combustor walls. A promising way to handle such thermal challenges is a transpiration/effusion cooling system where cold coolant enters the hot gas main flow through a porous wall and protects the porous segment as well as the wall portions downstream. This topic is also of great interest for rocket engine applications since similar phenomena might occur in transpiration/effusion cooled next generation nozzle extensions and combustor structures.

The test setup at M11.1 is used for investigation of the phenomena connected with transpiration/effusion cooling. Since wedge shaped struts are state of the art as flame holders in scramjet engines the influence and the interaction of such a strut with the hot gas main flow and the secondary coolant flow are subject to research. Shocks generated by flame holders and struts can interfere with the coolant boundary layer and the combustion chamber's walls which can lead to influencing factors, i.e. hot spots at the porous wall segment, inefficient cooling, shock-boundary-layer interaction, reactive boundary layer combustion processes and choking.

As part of such investigations a scramjet model combustion chamber is connected to a chemical air heater (air vitiator with use of makeup oxygen). An intermediary Mach 2.5 nozzle generates the inlet boundary conditions for the versatile model combustion chamber. It can accommodate an exchangeable wedge shaped strut, which can be positioned laterally and horizontally with a pressure tight positioning mechanism to induce different shock patterns (see Figure 1.85). The model combustion chamber (length 300 mm) can accommodate different measurement methods like Particle Image Velocimetry (PIV) and Schlieren optics. For this purpose it is possible to provide different combinations of optical accesses using quartz glass windows. One of the model combustion chamber walls can be equipped with a porous section (length up to 150 mm), which is supplied with coolant by a plenum. Gaseous and cryogenic coolants (such as pressurized air, liquid/gaseous nitrogen and gaseous hydrogen) can be used as well as different types of porous media.

The strut's geometry generates a shock pattern that interferes with the walls of the combustion chamber and with a possible porous wall segment (Figure 1.86). Experiments showed a strong impact of the wedge shaped strut on the choking sensitivity of the channel connected with the shock/boundary-layer interaction generated by the wedge's shocks. Despite this the wall downstream is well protected by the coolant film
and kept at moderate temperatures even with high temperature main flows and low coolant blowing ratios.

Figure 1.84: Air heater (vitiator) with attached Mach 2.5 nozzle.

Figure 1.85: Combustion chamber with wedge shaped strut

Figure 1.86: Coolant film and shock/boundary-layer interaction with supersonic flow (9.3° half wedge)

### 1.9 Nozzles

The convergent-divergent rocket nozzle transforms the thermal energy released in the combustion chamber to kinetic energy by accelerating the hot combustion gases to high supersonic velocities. It is the key driver for a high specific impulse resulting in thrust. It is the engine part which interacts with ambient conditions and has to be carefully designed depending on its specific operational characteristics.

Beside the choice of the fuel combination, three main operational scenarios exist and consequently require different nozzle designs needing detailed experimental and numerical studies: first stage or booster application, main stage application, and upper stage application.

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 achieve the maximum overall flight performance.

An important aspect of nozzle design is the structural load being induced during transient start-up of the engine and its full sea-level operation. Side loads occur due to flow separation and can lead to an undesired intensified flow-structure-interaction. These loads 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 limits the nozzle length and area ratio, and results in a loss of performance during the ascent phase of the rocket. These losses can be compensated for by applying innovative high altitude adaptive concepts like the dual bell nozzle.

Not only the complexity of the after body flow field of an ascending rocket have to be taken into consideration, also the interaction of the nozzle and ground test facilities and launch pads must be taken into account. The nozzle is therefore the rocket engine system part that has to meet both flight operation and ground testing requirements. Its research and technological development have to cover a wide range of different parameters including rocket and test facility requirements.

Experimental and numerical studies were carried out to increase the technology readiness level (TRL) of nozzle innovations starting with cold flow tests on test facility P6.2 and leading to hot flow tests on test facilities P8 and P6.1. This included studying the interaction nozzle/test facility.

### Flow Separation and Side Loads

The flow separation during the transient start-up process and the resulting side loads are of crucial interest. Cold flow subscale tests at test facility P6.2, either carried out under high altitude conditions
inside a chamber or under ambient conditions on a horizontal test rig, give a fundamental insight into nozzle flow phenomena (Figure 1.87 left).

Figure 1.87: Mounted TIC-2048 (left) and NPR and side load progress (right)

Particular parameters were studied in experiments carried out with ASL Ottobrunn to develop and validate side load models. The impact of the length of the separated backflow region, the wall contour angle and the total pressure gradient during start-up and shutdown process on side load generation were carefully examined. Three subscale models were designed and tested in five different configurations. A comparably slow moving separation front (Figure 1.87 right), passing a long and narrow backflow region with a low wall exit angle, could be identified as the main driver of the side load generation.

In addition two nozzles were tested of the same design but of different size. The experimental data confirmed that the scale of the separation length, and hence the side load scales with the scaling factor $k$ (Figure 1.88).

Figure 1.88: Comparison of separation lengths $L_{sep}$

The ratio of side load and thrust $F_{SL}/F$ therefore remains constant as predicted. The side load torque $T_{SL}$ acting around the nozzle throat increases linear with factor $k$.

The studies took place as part of the national research initiative Propulsion 2020.

Ceramic Nozzles

In the framework of the special research field SFB TRR 40 a team effort involving RA-RAK (LA) and BT KVS (ST) has been set up to investigate the application of C/C-SiC material in rocket nozzle structural design. Three nozzles sharing a common inner contour were produced and tested under similar conditions: a reference nozzle made from PMMA with very low wall roughness, a C/C-SiC nozzle extension with a metallic throat segment and ceramic extension, and a nozzle made completely out of C/C-SiC material (Figure 1.89).

Figure 1.89: Shock system outside of CMC nozzle visible through nitrogen condensation in the core flow

The higher degree of wall roughness occurring in the ceramic models leads to a nonlinear development in the separation front and an up-stream shift in its axial position. In this combination the level of increase in the side loads is acceptable.

In conclusion the ceramic nozzles have shown a satisfying performance. Future studies will have to confirm the performance under hot flow conditions and there are plans to carry out joint tests at P8 in 2017.

Nozzle Ovalization

Nozzle ovalization is a highly complex issue involving flow structure interaction. If the flow separates inside the nozzle, it intensifies the structural deformation. If a resonance frequency is excited, it might lead to a structural collapse.

Up to now there is a lack of experimental data to validate numerical analyses. RA-RAK (LA) and AöRFZ (BS) have appointed a joint team to study and better understand this aspect within the DLR ProTAU
project. The experimental work is being carried out also as part of the special research field SFB TRR 40.

Three nozzle geometries were deformed and tested under cold flow conditions. The test specimens were equipped with several pressure ports in order to measure the pressure distribution along various axial lines. In addition the exhaust flow was recorded using Schlieren optical techniques. The nozzles were rotated around their axis in 45° increments in order to observe the flow from different points of view and reconstruct the 3-dimensional shock system (Figure 1.90).

Nozzle Exhaust Jet Acoustics

The interest in the acoustics of nozzle exhaust jets increases as regards predicting and limiting the noise emission on test benches and on the launch pad. In addition this aspect contributes to better understanding the mechanics of resonance frequencies and their effect on the structure. The coupling of the flow and the nozzle structure can be the reason why vibrations are strong and side loads increase.

Test have been conducted on TIC nozzles at the P6.2 cold flow facility to identify and compare the main frequencies of the wall pressure, the side loads, the exhaust jet shock system and the related acoustical emission.

Experimental results confirmed the deformation of the separation line in a circumferential direction (Figure 1.91). The transformation of the relevant shock system from a planar Mach disk in non-deformed nozzles into a three-dimensional Mach "saddle" is clearly visible. The deformation decreases with increasing NPR. A sense of its three dimensional structure (Figure 1.92) can be gained by looking at the shock system from different angles.

The curvature of the Mach saddle and the deformation of the separation line depend on the NPR value, and are at their maximum shortly before the separation point reaches the nozzle end.

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Nozzle divergent geometry and varies only slightly with the total temperature. This indicates it originates at the nozzle throat region. A second recurring frequency was found around 1400 Hz and was directly proportional to the NPR. The frequency only appears at higher NPR values when the Mach disk has reached the nozzle end and once the shock system has left the inside of the nozzle. This frequency seems to be proof of a coupling effect between the flow and the nozzle structure. An additional frequency was detected when placing a sensor at the nozzle lip facing downstream. A perturbation with a constant frequency of 1105 Hz seemed to move in the upstream direction and could only be measured by this sensor. As part of the SILA project more work on acoustic measurements and analysis will be carried out to better understand these resonance frequencies. SILA is a joint project of the Test Facilities, Engineering and Rocket Propulsion Departments at DLR’s Institute of Space Propulsion.

Altitude Adaptive Dual-Bell Nozzles

The dual-bell nozzle, which is altitude adaptive, cuts into a conventional base nozzle and an attached nozzle extension, linked by the characteristic wall contour inflection. The constant or positive extension wall pressure profile enables a stable flow separation at sea-level and an abrupt transition to full flowing high altitude operation during the ascent of the rocket. It results in an increase in performance on ground as well as during ascent. The Ariane 5 would benefit from a payload gain of up to 490 kg if Vulcain 2 would be improved with a dual-bell.

The concept is being studied in cold and hot flow subscale tests at test facilities M11, P6.1, P6.2 and P8 as regards extension contour and contour inflection design (Figure 1.94), extension length scale, propellant combination, ROF variation, total pressure gradient, total temperature effects, film cooling application, and ambient pressure and density impact (Figure 1.95). Intensive studies came up with a reliable prediction of transition and related hysteresis characteristics.

Figure 1.95: Transition and retransition conditions as a function of the pressure within P6.2 high altitude chamber (left)

Figure 1.96: Thermographic images of the nozzle under sea-level and high altitude modes

The transition process with its accompanying contour inflection heat flux (Figure 1.96) and side load behavior may be regarded as understood. It has been proved that in addition to the total pressure variation, the transition can be triggered by changes in the ROF mixture ratio. Furthermore, a new flow state called sneak transition (Figure 1.97) and its influence on side load generation was detected.

Figure 1.97: Observation of the sneak transition in the extension region with color Schlieren optics

Experience in operating a film cooled subscale dual-bell nozzle under representative hot flow conditions (Figure 1.98) has been gained as a result of a test campaign using BKE and a Vulcain 2 like base nozzle.

Figure 1.98: Observation of the sneak transition in the extension region with color Schlieren optics
It came as a surprise to discover a reattached flow condition during engine start-up. This was found to be a consequence of the chosen low start-up ROF and can be avoided by changing the sequence in a subsequent test campaign as foreseen in 2017.

A hotflow LOX/CH₄ test campaign on the dual bell nozzle was carried out under a cooperation agreement between DLR and JAXA (Figure 1.99 left). The accompanying tests have led to the validation of the design method and transition prediction for hot flow conditions. The dependency of the transition and retransition pressure ratios with the ROF discovered in an analytical study could be experimentally proven (Figure 1.99 right). The decrease in transition and retransition NPR is almost linear as the ROF value increases.

This results in the possibility to control or trigger a dual bell transition during flight by varying the mixture ratio, which would have significantly less impact on thrust generation and trajectory compared to a severe change in combustion chamber pressure as suggested in past studies.

In addition, it was possible to demonstrate that a well-chosen nozzle extension design featuring positive wall pressure gradient allows the almost complete circumvention of the sneak transition, and hence limits the associated side load generation.

Parts of the dual-bell work presented are being performed within the frame of SFB TRR 40 as well as under ProTAU.

Work is ongoing to study the impact of ambient pressure fluctuations and extension nozzle ovalization on transition behavior, flow structure interaction, and the related side loads.

**Upper Stage Nozzles**

The expansion deflection (ED) nozzle is an unconventional upper stage nozzle. The advantages of its reverse flow configuration, where the combustion chamber is positioned inside the nozzle and the flow is redirected in 180 degrees, are that the engine length is halved and heat pickup increased, thus improving future expander cycle designs.

Detailed hot and cold flow tests were conducted on test facilities M11 and P6.2 using a planar ED nozzle where an elongated center body emulates the reverse flow design (Figure 1.100). The transition behavior from open to closed wake mode, its vice versa retransition (Figure 1.101), the resulting hysteresis, and the exhaust jet were studied in detail using optical and pressure measurements in the nozzle throat and downstream of the center body wake. Within the study, a base pressure rise within the hysteresis regime was detected (NPR 21.5 down to 18), which up to then had been unknown and had not been documented.
Side Load Reduction

The interaction of the nozzle and the test facility environment and the interaction within a high altitude simulation chamber in combination with a diffuser and an ejector stage was studied at P6.2. The areas of interest are transient start-up side loads and fluctuations induced by the test set-up. A side load reduction device is in the development phase (Figure 1.103). 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 need a thrust level variation on a test facility like P5.

Four ring shaped side load reduction devices (SLRD) were tested in combination with a TOP nozzle (Vulcain 2 like). The SLRDs were fixed all the time on the guiding tube. Varying the distance to the nozzle exit permitted a parametrical study.

All SLRDs reduced the FSS to RSS transition side load peak during start-up to less than half of the initial peak. The smaller the wall contour angle of the SLRD, the more the related peak is reduced and shifted to lower NPR.

Because SLRD B gave the best results the decision was made to select it to study the influence of the distance between nozzle exit and SLRD inlet on side loads. Figure 1.104 shows the related side loads. When the distance is increased the start-up side load peak also increases. The shutdown peak value in contrast decreases the longer the distance is, down to its initial value.
Test Bench Interaction

The separation characteristics of nozzles operated under sea-level conditions can be easily researched. Studying how a nozzle operates under altitude is much more complex. One alternative is to adjust the NPR to representative values at sea-level by increasing the total pressure. This procedure however disregards the decrease of ambient density during launcher ascent. For this reason tests were conducted at the P6.2 altitude simulation facility to study the influence of the ambient density on the flow separation in conventional rocket nozzles.

![Figure 1.105: Separation as a function of NPR and ambient density](image)

Results showed that the flow separation within rocket nozzles differs for altitude and sea-level conditions. Under altitude conditions the flow separation shifts upstream. If the NPR of a given flight altitude is simulated as an equivalent sea-level test, the resulting flow separation compared to real flight conditions shifts downstream.

1.10 Numerical Simulation of Flows in Rocket Combustors and at Test Facilities

During the design process of rocket engines and test facilities several design tools are applied. Starting with empirical methods and analytical approaches numerical flow simulations are used to gain a deeper insight into the physical processes of a rocket engine. This reduces the time and the costs for the design and development of a rocket engine and the dedicated test facilities.

Numerical flow simulations in the field of space propulsion have to cover a wide range of applications, from the cryogenic injection of liquids to the supersonic and reactive expansion of the combustion gases. Therefore, at the Institute of Space Propulsion commercial codes like ANSYS CFD and DLR in-house codes like TAU are used. Use of an in-house tool like TAU is always preferable because such tools don't depend on expensive licenses and ensure a more detailed insight into the solver code. Only the development of tools like TAU ensures that access to super computers for DLR becomes affordable. This is an essential aspect in the numerical simulation of rocket engines.

Numerical flow simulations of the processes in liquid rocket engines are still not able to capture all physical aspects by using only one model and one code. In fact the different disciplines use their own models and try to connect them by taking boundary conditions into consideration. One way to separate the different disciplines is to divide it into the following main subjects:

- Combustion chamber
- Cooling channels
- Nozzle flow
- Test facilities.

The Institute of Space Propulsion in Lampoldshausen includes all of these disciplines in its numerical flow simulation activities.

Combustion Chamber

The simulation of rocket combustion chambers has to cover a wide range of physical phenomena, from the real gas effects during the cryogenic propellant injection and the transient ignition process of the fuel/oxidizer mixture to the interaction of combustion and acoustic in the reaction volume.

One example for the numerical flow simulation of a combustion chamber is illustrated in Figure 1.106. The plot depicts the temperature field inside a combustion chamber with an API (Advanced Porous Injector) injection head developed at the Institute of Space Propulsion.
While the oxygen is still injected through pipes, the hydrogen enters the combustion chamber through a porous medium covering the face plate of the engine. Numerical analyses carried out have shown a higher heat release in the vicinity of the injection head compared to results from an engine with coaxial injectors. This aspect could be significant in the case of an upper stage engine with an expander-cycle like Vinci.

In order to predict the heat transfer into the combustion chamber wall detailed chemistry models have to be applied during a rocket engine flow simulation. The Institute is working on the development of such chemistry models. In particular, the complexity of reaction mechanisms regarding the methane oxidation has challenging implications on the necessary computational effort. Research is therefore taking place into reducing these complex methane combustion models to an affordable level.

Another field of numerical research is laser ignition in a GOX/GCH₄ combustion chamber. Due to the increasing interest in reusable space transportation systems the focus of the European space industry is more and more on the application of methane as a fuel. Using a laser ignition system instead of a pyrotechnic solution would ensure the re-ignitability of the engine and would reduce engine mass and safety requirements. Numerical analyses of the laser ignition of a GOX/GCH₄ mixture are therefore being conducted to reach a better understanding of the processes during the start-up transient of a GH₂/GCH₄ engine with a laser igniter. In detail the flame speed after ignition and the pressure peak inside the combustion chamber are of special interest. These parameters for example depend on the conditions of the injected propellants or the time of ignition after opening the propellant valves. Figure 1.107 illustrates the comparison between the numerical flow simulation of flame propagation and Schlieren images obtained by experiments at DLR’s M3 test facility.

The validation of the numerical models using experimental data ensures the reliability of the developed models. Therefore, maintaining a close alliance between experimental and model designing activities is essential.

In the past combustion instabilities have often been the reason why missions and testing of space propulsion systems have been unsuccessful. These combustion instabilities are the result of a combination of combustion processes and acoustics inside the engine. Research into these physical coupling processes has not yet been fully completed and they are therefore not yet completely understood in detail. For this reason the Institute is carrying out appropriate numerical analyses. Figure 1.108 shows the influence of an acoustic velocity excitation on the flame of the BKH combustion chamber as a result of a numerical flow simulation using TAU. BKH was designed to investigate combustion instability mechanisms under realistic operating conditions. The combustion chamber can be excited by using a nozzle.
wheel system to observe flame/acoustic interaction. It has a quartz window and a sensor array. For the numerical investigation the cryogenic oxygen had to be treated as a real gas.

During the development of the numerical BKH model, the TAU flow solver had to be upgraded with the capability to handle real gas effects in the combustion chamber.

Cooling Channels

One of the main challenges during the design process of a rocket engine is the cooling of the combustion chamber walls. During operation of a LOX/LH₂ rocket engine the temperature of the hot gases inside the engine reaches more than 3500 K.

Therefore, the combustion chamber has to be cooled. Often regenerative cooling is applied, where one of the propellants streams through cooling channels along the combustion chamber walls. Here the cooling effect depends on the aspect ratio of the cooling channels. Figure 1.109 depicts the results of numerical simulations which investigated the impact of different cooling channel aspect ratios on the temperature of the chamber wall.

Nozzle Flows

One of the research fields at the Institute is the supersonic expansion of the combustion gases in the thrust nozzle of a rocket engine. The flow group in the Rocket Propulsion Department conducts detailed numerical investigations of the flow transition behavior in dual-bell nozzles. It combines the advantages of a small area ratio nozzle under sea-level conditions and a large area ratio nozzle under high altitude conditions. The nozzle consists of two bell shaped nozzles linked by a sudden change in wall angle at the contour inflection.

Under high ambient pressure conditions the contour inflection forces the flow to a controlled and symmetrical flow separation. Figure 1.110 illustrates a full 3D simulation of the flow field of a dual-bell nozzle in sea-level mode. During the ascent of a launcher the ambient pressure decreases. When a certain ambient pressure is reached the flow separation position moves abruptly downstream to the nozzle exit. This results in a performance gain as the combustion gases are further expanded. Sea-level and altitude mode of the dual-bell nozzle are well studied and stable operational conditions. Activities in the field of numerical analysis of the Institute focus on the transition process from one mode to the other.
Therefore URANS simulations of the dual-bell flow transition process are conducted using DLR’s TAU flow solver.

The composition of the combustion gas coming from the combustion chamber has a strong impact on the flow transition process of a dual-bell nozzle.

Numerical simulations are conducted to investigate the impact of the combustion chamber mixture ratio on transition behavior of the dual-bell nozzle. Figure 1.111 illustrates the comparison of the Mach number distribution applying two different numerical chemistry models for the $\text{O}_2/\text{CH}_4$ combustion in the hot gas nozzle flow. One result of these simulations is a potential controlling or triggering of the dual-bell nozzle flow transition by small changes in the propellant mixture ratio.

Test Facilities

The Department of Engineering uses numerical simulations as an engineering tool. During the design process and the operation of the test facilities numerical flow simulations are applied to gain a deeper insight into the behavior of the test facilities and the test specimen. The numerical tools used here are already validated for their specific application to provide reliable data for the design and operation of rocket engine test facilities. Figure 1.112 illustrates the instantaneous Mach number distribution during the shutdown process of the Aestus engine at DLR’s P4.2 test facility. The simulations were performed to gain a more detailed understanding of the flow processes in the core diffusor and the high altitude chamber of the test facility. Especially the core diffusor is one of the most critical components of the P4, high altitude simulation test facility, because of the extremely high thermal loads emanating from the combustion gases of the engines operating inside the high altitude chamber.

TAUROS

TAUROS is a future project carried out in a combined effort between the Institute of Aerodynamics and Flow Technology, the Institute of Combustion Technology and the Institute of Space Propulsion. The project focuses on the future development of the in-house flow solver TAU and intensifies the cooperation between scientists working on numerical and experimental analyses, thus ensuring the generation of high quality experimental data for the validation of the numerical flow simulations. The aim of the project is to develop a reliable tool for the future design and simulation of space propulsion systems because commercial tools are limited. Such a tool would give the DLR independent competence in modeling and simulation of rocket propulsion systems and the related components. The Institute of Space Propulsion is in charge of and manages the TAUROS project.

Four fields of activities are identified and integrated into the TAUROS project. The following development steps for the CFD code TAU are planned:

- Combustion chamber: One goal of the main combustion chamber work package is to implement a real gas flamelet model in TAU. This model will be validated using experimental data.
from a single injector test campaign conducted at P8. The TAU simulation results will be compared with high order simulation results from the Institute of Combustion Technology. Furthermore, combustion instability effects are being investigated as part of the work package. For this reason the TAU code has to be upgraded with several new modules. These modules are applied during the post processing step of numerical data input and help establish a better method for the comparison with experimental data.

- Thrust nozzles: In the main work package concerning thrust nozzles the flow behavior of deformed TOP nozzles will be investigated. Therefore, the structure solver NASTRAN will be coupled with the DLR's flow solver TAU to investigate the flow/structure interaction of TOP nozzles under separated flow conditions. The second focus of the work package will be the correction of the implemented Reynolds stress model to reduce an unphysical high production of turbulence behind strong shocks in a supersonic flow field. The corrections to this turbulence model will be applied on a LOX/CH4 dual-bell nozzle flow transition simulation to investigate the impact of the modifications.

- Test facilities: The main work package test facilities will draw on the expertise of the other work packages to apply TAU code on a real test facility case. In detail TAU will be used to model the gimbal process of the Ariane 6 upper stage engine Vinci inside the high altitude simulation test facility P4.1. In addition the first steps for research into acoustic effects at the test facilities and on the specimen will be carried out.

- Thrust chamber wall cooling: In the main thrust chamber wall work package cooling simulations will be conducted to investigate the impact of different cooling channel aspect ratios on the cooling of the combustion chamber wall. Therefore a case from an experimental test campaign conducted at the P8 facility will be defined and simulated with the TAU code. The code must therefore be validated for application with transcritical and supercritical fluids inside cooling channels.

The TAUROS project intensifies a long term team effort in order to further develop and validate TAU and therefore strengthen the competence of DLR in analyzing and evaluating launcher systems and their components.

**HyNOx Combustion Chamber Processes**

To gain a better understanding of the processes inside the HyNOx model combustion chamber simplified numerical simulations with implementation of the reaction processes are carried out. DLR's TAU Code is used in combination with reduced reaction schemes for the combustion of the N2O/C2H4 mixtures. The reaction schemes were derived by the DLR Institute of Combustion Technology in Stuttgart as part of the Future Fuels project. To resolve all occurring elementary reactions, huge computing capacity would be required, resulting in time-consuming studies until convergence is reached. Thus reduced reaction mechanisms with adequate description of the ongoing processes are essential to obtain qualitatively good simulations in acceptable time. The ignition process of the gaseous mixture is simulated and the results will be compared to experimental shock tube experiments carried out by the Institute of Combustion Technology. Furthermore simulations of the combustion process inside the chamber (chapter 1.4) will take place.

A first simulation included the injection of the premixed gaseous nitrous oxide and ethylene. Here the flow field for an impinging jet injector already used for experiments was analysed. Simulations of the general flow field should deliver the basis for later simulations with the combustion and reaction models enabled.

![Flow field simulation with gaseous injection](image)
1.11 Diagnostics and Measurement Technologies

Optical diagnostics bring together measurement techniques and analyzing tools for photon radiation phenomena ranging from ultra-violet energy to the field of infrared thermal radiation. However, studying the application of optical diagnostics in highly turbulent rocket combustion chambers remains challenging and differs from implementation under ambient conditions. Extreme flow conditions in combustors with pressures of up to 300 bar and temperatures of up to 3600 K demand special development of the set-up configuration and construction. Measurement devices have to be cooled and completely protected to cope with heat and other destructive influences. High temperature and pressure values cause spectroscopic measurements to give extremely biased responses due to densely populated ro-vibrational states in the molecules involved.

Nevertheless, recently developed optical measurement techniques adapted for model combustors are nowadays regularly applied for full scale rocket engines at the P3, P4 and P5 test facilities in Lam- poldshausen.

Visualization Techniques

High-speed imaging techniques are applied in order to reveal crucial phenomena that take place over a very short time scale. Movie recording with a high temporal resolution delivers an insight into ignition processes, flame propagation, and combustion instabilities. Using intensified optics, ultraviolet radiation can be made visible. The front of flames containing hydrogen is investigated in this way using the emission of the OH* radical. Figure 1.114 shows both visible and ultraviolet emission of the Vulcain 2 plume. This test took place at P5.

Schlieren optics and shadowgraph techniques are standard methods used for visualizing flow topologies and the distribution of the liquid phase in multi-phase flows. These are indispensable tools for looking into atomization processes and optical injector characterization. Both intensified and non-intensified image devices increase scientific knowledge about all kinds of combustion phenomena. Furthermore, nozzle plume diagnostics of several full scale rocket engines have been carried out using high-speed camera systems.

Image processing tools such as Abel transform algorithms are used to visualize flame shape and emission zones. This method takes advantage of the cylindrical geometry of the injection process. At the “Mascotte” test bench at the ONERA test facility in Palaiseau, France, experiments on various injector geometries have been carried out. The results are shown in Figure 1.115. The Abel transformation demonstrates the injector performance very well.

At P6.2, a cold flow test facility, high speed Schlieren imaging is performed to visualize, for example, the shock pattern of dual-bell nozzle plumes in order to determine the transition and retransition duration from sea-level to altitude operation mode (see Figure 1.116). The location and angles of the shock pattern can be read out of the Schlieren images and are used for validation of the numerical results.

Figure 1.114: Plume of Vulcain 2 engine, recorded in the visible (A) and ultraviolet (B) domain.

Figure 1.115: Coaxial swirl injection. The ultraviolet emission of the LOX/GCH₄ combustion is visualized using averaged image (A) and Abel transform (B).

Figure 1.116: Coaxial swirl injection. The ultraviolet emission of the LOX/GCH₄ combustion is visualized using averaged image (A) and Abel transform (B).
Flame Spectroscopy

Discrete atomic and molecular energy levels absorb and emit well defined photons that are used to characterize substances and chemical reactions. Due to their intense emission it is easy to examine flames spectroscopically. At P8 the LOX/GH₂ combustion process was investigated using a high-resolution spectrograph for collecting emission measurements in the BKD combustor. Sapphire probes provided an insight (line of sight) into the reaction zone.

As depicted in Figure 1.117 it was possible to gather spectral information from a highly turbulent flame. According to prior findings spectral features within this range are suitable to derive flame temperature due to the existence of invariable emission bands sensitive to temperature change. Moreover, the flame temperature deduced as a result is in excellent accordance to numerical models developed using ANSYS software.

The dependency of pressure in the emission of a LOX/GH₂ combustion process was demonstrated during a P8 test campaign using BKD. Results are shown in Figure 1.118. For pressure values between 40 bar and 80 bar it is clear that intensity of emission in the visible spectral range increases as the pressure is increased. At the same time the intensity in the ultraviolet range remains nearly constant. In cooperation with researchers from TU Munich this behavior in connection with low-pressure flames was also investigated.

Moreover, emission and absorption spectroscopy was carried out at the P2 test bench to examine the hypergolic MMH/NTO combustion processes. The side effect emission of the Na d-line was used for flame temperature measurements.

Laser-Induced Breakdown Spectroscopy (LIBS)

Plasma can be characterized by the radiation it emits. For this reason laser-induced ignition sparks were analyzed in order to obtain information about the local mixture ratio, plasma temperature and rate of electron density. Figure 1.119 illustrates the ignition process from the plasma sparking to steady combustion using an encased camera located downstream of the combustor nozzle.

At the P8 test bench a laser ignition test campaign was conducted using the BKA combustor and a LOX/GCH₄ or LOX/GH₂ propellant mixture. Whereas...
injection parameters are generally known, the local ROF at the exact spot where ignition takes place remains unclear due to the highly turbulent state of the three-phase-flow inside the combustor. Precise numerical simulations are very complex and not available at the present time.

Figure 1.119: Ignition process on the multi-injector faceplate of BKA. The white arrow on the left figure indicates the laser-induced ignition spark.

A time series of LIB spectra (Figure 1.120) clearly shows the influence of hydrogen and oxygen on the ignition process within the plasma spark. Ignition takes place if both are detectable. Furthermore, quantitative LIBS analyses on well-defined gas mixtures in a laboratory cavity revealed equivalence ratios for the moment of ignition within the plasma of about 35. Using Boltzmann and Saha equations it is possible to derive the plasma temperatures. The intensity of three hydrogen lines of the Balmer series delivered plasma temperature levels of more than 8500 K.

Figure 1.120: Time series of LIB-spectra correlated to the corresponding laser pulse. Ignition takes place if both hydrogen and oxygen are detectable.

**IR-Thermography**

Using state-of-the-art IR camera systems accurate temperature mapping on space propulsion hardware is routinely conducted during test campaigns at the P8 as well as at the P3, P4, and P5. Figure 1.121 depicts thermography images of the nozzle extension of the Ariane 5 upper stage engine Vinci.

Moreover, particles in exhaust plumes also deliver thermal information due to their ability to emit long wave infrared radiation according to Planck’s law. At the P8 experiments on the plume of sooty combustions have therefore been conducted and analyzed.

Figure 1.121: Thermography on the Vinci nozzle extension during test under vacuum conditions P4

**Time-Resolved Flame Emission**

Filtered flame emission of two narrow optical regimes has been analyzed highly time-resolved. Both spectral windows with $\lambda = 306$ nm and $\lambda = 430$ nm correspond to decisive phenomena of flames containing hydrogen and oxygen. The origin of the ultraviolet emission is the well-known OH* radiation. On the other hand the emission of the visible photons around 430 nm stems most probably from H$_2$O$_2$ molecules. Using sapphire probes which are resistant to the effects of temperature changes and photo-multiplier electronics equipped with optical band-pass filters high-frequency analyses with a repeat rate of 100 kHz were conducted. Furthermore, these optical responses were compared with measurements of dynamic pressure. No significant differences could be observed. As illustrated in Figure 1.122, the emission of the plasma decay induced by the ignition laser system is clearly visible. Furthermore, the combustion can be monitored and the time from combustion start to engine shut-down (ceased combustion) is identifiable. A frequency analysis revealed, moreover, an oscillation rate of around 950 kHz. Both the
integrated optical emission and the corresponding signal flickering comply with dynamic pressure measurements. This verifies again the correlation between pressure and flame emission.

Figure 1.122: Dynamic sensor data (left) and the corresponding FFT analysis (right) of a laser-ignited startup test in BKA. Diagrams A and B show the intensity of the narrow optical band around 306 nm. C and D represent radiation at 430 nm. Results of pressure measurements are depicted in diagram E and F.

**Optical Deformation Measurement**

The deformation of an ambient pressure test specimen such as e.g. a TMF panel is determined by an image correlation system based on photographs recorded with the stereo camera system shown in Figure 1.123. In order to obtain the highest possible accuracy in the measurements, a system consisting of two 16 MPixel cameras was selected. This measurement system requires applying small speckle marks to the surface of the test specimen and allows for the measurement of a 2D, 3 component displacement with a measurement uncertainty of less than 5 µm.

Figure 1.123: Stereo camera system for deformation measurement.

An exemplary result of a deformation determined with this optical stereo camera + image correlation system is shown in Figure 1.124.

**Absorption Measurements**

The absorption of a laser loaded surface at elevated temperatures is determined by comparing measurements recorded with thermocouples to measurements recorded by a pyrometer with an identical wave length as the laser. High end transfer standard pyrometer, like the IMPAC 512-TSP shown in Figure 1.125, allow for temperature measurements with an accuracy of ± 0.15% of the measured value ± 1°C at a measurement range between 430°C and 1300°C.

Figure 1.125: Laser wave length pyrometer

An exemplary result of the determination of the time dependent emissivity of the TMF panel coated with ARA using this laser wavelength pyrometer is shown in Figure 1.126.
2D Laser Heat Flux Distribution Measurement

To determine the heat flux into a laser loaded structure, the following values have to be measured:

a. the absorption of the laser loaded surface at the laser wavelength
b. the total optical output power of the laser
c. the laser power distribution on the focal plane of the laser beam.

In the case of:

a), the laser wavelength pyrometer as shown in Figure 1.125 is used, for b) and c), the laser power meter and the beam profiler as described below are used, respectively.

Laser Power Meter

A special version of the PRIMES Power Monitor with an aperture of 250 mm x 50 mm as shown on the left-hand side of Figure 1.127 measures the total optical output power of the TMF laser. For total optical output laser power values between 1 kW and 12 kW, the measurement uncertainty of the system is smaller than ±2% of the measured value.

Beam Profiler

The distribution of the laser power in the focal plane of the TMF laser beam is determined by the PRIMES laser Beam Monitor BM 100 as shown on the right-hand side of Figure 1.127 with a resolution of 128 x 128 pixels and a measurement uncertainty of smaller than ±3% of the measured value.

1.12 Investigations in Testing Technologies

From the very beginning, Lampoldshausen has been involved in the development of all of the European launcher programs and one of its main tasks has always been the design, construction and operation of liquid rocket propulsion test facilities. There is a need to develop, qualify and accept propulsion systems within the flight loads and mission requests.

The Engineering department provides the full system competence for the design and construction of all Lampoldshausen test benches. Competencies of strategic importance for testing are the operating...
behavior, the high altitude simulation, the hot gas exhaust systems, the cryogenic and gaseous feed systems especially with stage-like supply conditions and standardized or customized measurement, control and command systems requested by the user.

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

Testing in Flight Conditions

“Test as you fly” means testing with stage like supply conditions, environmental conditions as in flight, basically vacuum and the simulation of flight loads.

The acceptance process of the high altitude simulation facility P4.1 with the new upper stage engine VINCI including the large extendable nozzle has demonstrated the special know-how for the Institute of Space Propulsion in Lampoldshausen.

The task of altitude simulation consists of creating the test condition of just a few mbar within a vacuum cell. 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 operated by alcohol and oxygen.

The challenges for the P4.1 altitude simulation are the use of adapters to test different test configurations on the same test position, the use of a center 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.

Due to the modular design connecting the new VINCI nozzle to ARIANE 6 was easily handled by using a new adapter.

The center body diffuser was developed first by a cold gas model of scale 1:18 for basic investigations of flow conditions and the function of gimballing of the engine inside the diffuser. Second a hot gas model of scale 1:8 was built for the verification of the head loads and internal cooling system. There were similar combustion conditions like during tests with the VINCI engine, means H2/O2 combustion with chamber pressure up to PC = 60 bar and mixture ratio ROF = 6, mass flow m = 1,8 kg/s.

The final step was the improvement of the manufacturing process for the verification of the stresses and the cycling loads in close cooperation with the supplier.
The current core of the diffuser has reached the lifetime. An innovative core was therefore designed with a new coating to withstand adverse thermal effects and improved welding techniques were used to increase durability. The center body was modified for the modular replacement. For the future the center body can be easier exchanged. The subsequent test campaign was successfully performed and the values were within the predicted parameters.

Figure 1.131: Life Time Conditions of the P4.1 Diffuser

The operational state of altitude simulation is ongoing investigated. The test data are used for the prediction of the static and dynamical conditions with respect to the test requests and even out of the nominal operating area.

Challenges are the strong throttling (< 10%) of the engine to verify the deorbiting maneuver or the ignition by subcooled LOX (< 85K). The test results were successfully predicted and the tests were performed.

The adapter from the VINCI testing was investigated using CFD calculations and test data to validate the conditions for gimballing the engine. The gimballing tests will be performed stage like, means with original propellant flight lines as close as possible to proper flight conditions.

Figure 1.132: Analyses of the adapter P4.1 by CFD to the footprint of the surface.

The conditions and loads in case of 1° displacement were investigated for the verification of possible risks.

Figure 1.133: VINCI engine with 1° displacement at P4.1

There are interesting challenges for the high altitude simulations. Examples are tests with lander engines operated in a wide range of 10% to 100% of thrust, a flight trajectory starting at sea level with shut down under vacuum conditions, new propellants for satellite propulsion to replace hydrazine, the reusability of rocket propulsion or advanced nozzle design like dual bell nozzles.

To look ahead the advanced altitude simulation AAS-P8 at the P8 facility was developed and erected. The purpose is to investigate components on system level in “hot conditions”, to develop the technologies for flow conditions externally surrounding the nozzle and plum, to verify operational conditions, to apply diagnostics like BOS (background oriented Schlieren) and of course to test experimental thrust chamber models. A special task is the interaction of advanced nozzle designs and the supersonic diffuser during transient conditions.

The basic operational parameters are a hot gas jet up to 4,5 kg/s, vacuum conditions during hot run down to 100 mbar, surrounding flow up to 7 kg/s air or N2. The actual operational range of the H2/O2 thrust chamber is 75 bar to 115 bar and mixture ration of 5,5 up to 7,5. There are two water cooled nozzles with extension area of $\varepsilon = 100$ (max.) and $\varepsilon = 57$ (VULCAIN like) available.
Actual there are modifications at the AAS-P8 to test the BOREAS thruster in close cooperation with CNES. The test campaign is scheduled for 2017.

**Testing Technologies and Legal Requirements**

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 has been developed for the research in noise reduction by special water injection. There are test campaigns since 2011 to investigate and improve the function.

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.

The noise emission without and with guiding tube could be reduced up to 20 dB(A). It is depending on the subscale combustor specially the nozzle expansion rate and jet velocity. The frequencies are different influenced by noise damping. Lower frequencies are not influenced.
The departments for Rocket Testing VEA, Engineering PTE and Rocket Combustion RAK have started a common project SILA (Side Loads and Acoustics) in rocket engines. The common interests are investigations in the interaction between the exhaust hot gas jet and the test bench. Actually it’s focused on the noise emission and side load generation and their possible reduction through implementation of special devices. First the evaluation will be improved for better understanding of the noise generation, distribution and evolution. The results will be used to implement and verify a CFD modelling for the prediction of the noise field. PTE is preparing a dissertation linked to this topic. PTE’s task in the project is a further investigation to improve the exhaust gas guiding systems for reducing the noise emissions. RAK has worked to investigate the side loads by flow separation. By a special device the side loads will be reduced. VEA is interested in the operational impact.

The radiation of the hot gas jet at the AAS-P8 and at PS was investigated during a student internship. The effect of heat loads are one of the driving parameters for the design of the test position with all the implicated installations. Besides heat conduction and convection the radiation is one of the sources for heat loads. Especially inside a vacuum chamber the radiation is a key factor. A simple model for the radiation loads was constructed based on information found in scientific literature and validated by heat flux measurements. The basic paper was “Infrared Radiation from Combustion Gases” C.B. Ludwig, W. Malkmus, J.E. Reardon, J.A.L. Thomson; National Aeronautics and Space Administration (1973)“. One of the critical input parameters are the temperature distribution and jet geometry of the hot gas jet. By a CFD calculation the surface of the hot gas jet was characterized.

The prediction of the radiation heat loads was about 250 kW/m², the measured values were 150 kW/m² max. The hot gas model has to be improved later on. One of the criteria is real 3-D effects of the jet modelling, actually the jet is calculated axially symmetric. Another one is the boundary layer of the free jet with the mixing of air and hot gases.

These improvements were confirmed by the investigation of radiation inside the test chamber of the advanced altitude simulation system AAS-P8. The difference of predicted radiation and measured values are linked to the ambient pressure conditions.


Safe Handling of Propellants

A basic requirement for carrying out hot firing tests is the safe operation during the complete work-cycle from production on to testing and to waste management. As a part of this task safety concepts for working with new energetic materials, advanced components and already existing storable propellants have to be drawn up for the research facilities.
These issues are the first step on the way to tests of propulsion systems. The handling and working rules developed have to be assessed and extended for the operational range in larger engine development and qualification test facilities or space propulsion systems.

As for example the production, testing and pre-qualification of propellants, materials or components are performed in the physico-chemical lab, the G49 production/preparation facility and at the M11 test positions.

![Figure 1.142: View into the propellant facility in G49.](image)

The applied safety conditions at these facilities are subject to high-level requirements:

- Personnel is experienced in the handling of potentially explosive or toxic materials,
- Personnel safety equipment is customized,
- Special risk management and alarm plans are in place,
- Production processes are remote-controlled.

These efforts are rewarded regularly by visits from external institutions and quality certifications (DIN ISO 9001:2015 and DIN ISO 14001:2015). The experience and preparatory work gained from such practices are important requirements for the safe handling of propellants and offer a source of excellent preparation for all the test activities and other scientific purposes.
2. Engineering and Operation of Test Facilities

2.1 Test Facilities Overview

2.1.1 Introduction

There has been a site at Lampoldshausen for testing rocket propulsion systems since as early as 1959 when the facilities at P1 and P2 were first erected. Later on in 1963 P3 and P4 were added in line in the frame of the European Launcher Development Organization (ELDO).

Lampoldshausen can look back with pride that all of these test facilities are still in use today. Equipment is being continually adapted and modernized to ensure that a state-of-the-art standard of technology is available at all the test benches on site. When the ELDO program was stopped a new era began in Lampoldshausen with the development of the Ariane launcher family.

The European Space Agency (ESA) is responsible for the successful performance of the Ariane program. Several facilities in Lampoldshausen actually appear in ESA’s asset portfolio and the obligations and rights of the two entities are regulated in the so-called ESA-DLR asset agreement. This agreement has been in place continuously since 1975 and is based on the regulations dating back to the time when the ELDO contracts were in force.

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

The decision in 1987 to develop the Ariane 5 launcher had a huge impact on Lampoldshausen: the test facility P5 went into operation in 1990 with the new necessary cryogenic infrastructure. The P5 has then been used for the development and qualification of the Vulcain main stage engine. Additionally P4.2 was adapted in order to be able to test the new upper stage engine AESTUS.

Since the site was opened in 1959 the test facilities have kept pace with the requirements needed in order to perform different testing activities for various programs. The level of know-how and experience at DLR in Lampoldshausen was always and still is extremely high and the test site became indispensible in the development of the Ariane 1 to 4 and Ariane 5 programs (see Figure 2.1).

![Figure 2.1: Test Facilities at DLR Lampoldshausen for Ariane 5 launcher and payload.](image)

The decision made during the ESA Ministerial Council in 2014 to develop a new launcher, the so-called Ariane 6, means that the DLR test site in Lampoldshausen is again crucial for the success of this new low cost launcher. P4.1 and P5 test facilities and the newly developed European Upper Stage test facility P5.2 which is now being erected are being used intensively during the development phase of Ariane 6. The P5 systems are now being adapted to accommodate the modified Vulcain 2.1 engine for Ariane 6 and development tests of the Vinci upper stage engine are currently running successfully at the P4.1 facility.

Also, for future programs such as the development of a potential LOX-Methane Launcher, the DLR test site at Lampoldshausen will play a major and very important role due to its unique experience, know-how and the unique test facilities. DLR Lampoldshausen needs to continue its successes in order to ensure success especially for the European launchers and programs.
### 2.1.2 Overview of the test site and facilities

The following pages contain an overview of the site of the DLR test center in Lampoldshausen. The facilities are described in more detail in chapter 2.4.

- **D22** Nitrogen Supply Facility
- **D38** Fuel Station
- **D40** Fresh Air Station
- **D41** Compressor Station and Material Store
- **D57** Hydrogen Compressor Building
- **D57A** P5.2 GN2 production facility
- **D59** Central Electrical Supply Installation
- **D61** Auxiliary Building for P6
- **D68** Control Building for P8
- **E15** Transformer Station
- **E24** Transformer Station
- **G3** Spare Parts Storage Hall at P3
- **G17** Equipment Building
- **G31** Fuel Station Building
- **G35** Workshop Building
- **G36** Fire Station
- **G46** Auxiliary Building
- **G47** Auxiliary Building
- **G48** Material Stock
- **G49** Material Stock
- **G52** Garages
- **G55** Stock
- **G56** Control Building Supply Facilities
- **G60** Auxiliary Building T58
- **I1A/B** Office Building
- **I1C** Site entrance and office Building, DLR Space Propulsion Forum with exhibition and DLR School Lab
- **I2** Office Building
- **I44** Office Building
- **M3** Laboratory and Office Building
- **M6** Measurement Building
- **M7** Control Building P3
- **M8** Control Building P4 and P5
- **M9** Assembly Building
- **M10** Workshop Building
- **M11** Test Facility and Office Building
- **M12** Stock
- **M27** Assembly Building
- **M28** Material Store
- **M29** Assembly Building
- **M30** Assembly Building
- **M50** Electrical Workshop
- **M51** Test facility
- **M54** Laboratory
- **M61** Office Building, Workshop
- **M70** Laser laboratory
- **N25** Sewage plant
- **N32** High water tank
- **N33** High water tank and re-cooling system
- **N34** Underground Water Gallery
- **N34A** Underground Water Gallery
- **N39** Decontamination plant
- **N45** High water tank
- **N63** High water tank
- **N63A** High water tank
- **N67** Supply Building
- **P1** Test Facilities 1.0 to 1.6
- **P2** Test Facility
- **P3** Test Facilities 3.1 and 3.2
- **P4** Test Facilities 4.1, 4.2, Steam Generator
- **P5** Test Facility
- **P5.2** Test Facility
- **P6** Test Facilities 6.1 and 6.2
- **P8** Test Facilities 8.1 and 8.2
- **T13** Solid fuel depot
- **T16** Acid depot
- **T18** Acid depot
- **T19** Acid depot
- **T20** Fuel depot
- **T21** Fuel depot
- **T23** Oxygen depot
- **T53** Stock
- **T58** Hydrogen depot
Figure 2.2: Overview facilities at DLR Test Center
2.2 Test Facility Development and R&T Support

The test facilities are developed in close cooperation of the Engineering Department PTE and the Test Department VEA. There are new test facilities like the upper stage test facility P5.2, there are extensions of test positions, there are modifications and adaptations of test facilities like for the VINCI high altitude simulation P4.1 and there are support activities for research and technology developments.

DLR Lampoldshausen provides the system competences for operation, design and erection of the test benches for liquid rocket propulsion. Besides the technical core competences mentioned in the chapter testing technologies there are competences like technical project management or approval planning with external engineering support requested.

2.2.1 New Test Facilities

One of the first tasks for the P5.2 upper stage test facility was the clarification of the requirements for the test facility set up and the essential design parameters and costs. DLR Lampoldshausen was a member of the ESA working group for their technical experience. It was necessary to clarify the test environmental conditions. There were requests to be “Kourou” like, for safety measures and operational conditions. Supported by various studies of DLR and in close cooperation with ESA and ASL the specification of the test bench was defined.

Special attention was paid to the safety measures in case of a malfunction of the stage. The P5.2 was designed for the A5-ME upper stage with a common bullhead. A huge mass of hydrogen and oxygen can be detonated. Various studies were carried out to determine the necessary safety measures. The safety distance for human (blast limit 35 mbar) is calculated to 550 m by NASA Hydrogen Manuals or “Yellow Book”. The location of the P5.2 was chosen with respect to the safety distance. According to the CFD “FLACS” calculation together with the recommendations of the EMI (Ernst Mach Institute), the safety distance as regards damage to property (blast limit 100 mbar) is calculated at 165 m. P5.2 was designed taking into consideration that P5 is nearby. High walls were strategically placed for protection.

2.2.2 Renewals and Upgrades

Test facilities are modified continuously to take varying test requests or renewals and upgrades into consideration. The center body of the P4.1 diffuser was exchanged and improved as described in the Testing Technologies chapter. Between two test campaigns the old center body had to be cut out, the interfaces had to be modified and the new center body had to be inserted. Several studies were carried out to discuss with the supplier the possible working process and mounting plan.

Due to the limited space the parts were handled through the vacuum chamber at the test position. Special protection devices, welding machines and tools were necessary for the exchange.
2.2.3 Technology and Research Support

Technology support involves the design and procurement of test hardware and components for test facilities in close cooperation with the researcher and operator, the verification of what hardware is available on the market, especially in the field of MCC and the improvement of processes. These activities mostly relate to the labs, the calibration labs of sensors and equipment, the electronic lab and to the design department and workshop.

New types of amplifiers will be used on the P5.2 test bench. Two potential suppliers IMD and Dewetron were under consideration. Sample amplifiers have been tested in the DLR electronic laboratory in order to assess their test bench compatibility as well as performance characteristics. The figure shows, that the filter steepness of the Dewetron amplifier (green) is not as good as that of the other amplifiers. It also can be seen, that the higher frequencies are not cut off completely and signal artefacts can be seen.

One of the problems associated with cryogenic test benches is to find a temperature sensor capable of measuring cryogenic temperatures down to 4 K for liquid helium.

A new temperature sensor DT – 670, a silicon diode, produced by the LakeShore company has been tested and characterized in the conditioning cabinet at temperatures down to 0°C. Silicon diodes provide a higher degree of accuracy and precision, than resistance thermometers.
In addition to being able to measure temperatures down to 4 K the sensor also has to withstand high pressures. In order to assess the sensor’s suitability the new LakeShore sensor will be used on the test bench P8 as an additional measurement link. To be able to do this the sensor needs an electrical supply of 10 µA, which is not standard supply for a test bench. To implement the electrical supply of 10 µA, a special power supply was designed and built in cooperation with an external company.

Background Oriented Schlieren (BOS) is a relatively new technique for flow visualization that has become available through modern image processing methods. Like other Schlieren techniques it is based on the deviation of light rays due to spatial variations in the refractive index of the investigated medium. However, in contrast to conventional Schlieren techniques, the BOS technique has a very simple setup and does not require expensive mirror optics that induces field-of-view limitations. The basic setup of a BOS system consists of a digital camera, a computer for data acquisition and a background with a semi-random pattern to make the light ray deviations visible.

Currently a new BOS system is under development at DLR Lampoldshausen with the focus on compactness and flexible use options (Figure 2.10). The system features a USB 3.0 powered camera with a resolution of 2448 x 2048 pixels at a framerate of 75 Hz. This allows to capture also high dynamic processes.

In contrast to conventional Schlieren techniques horizontal and vertical components of the light ray deviation can be measured at the same time.

The new system is scheduled to be tested with the development of the P5.2 H₂O₂ burner.

The H₂O₂ burner will be used at the P5.2 to burn H₂ in the air for safety reasons. The burner is produced in additive layer technique. The design and procurement was done by the PTE department, the qualification will be carried out at M3 in close cooperation with the RAK department.

For investigations in turbo pumps an inducer and impeller were designed and produced by the design department and workshop in close cooperation with the scientists involved.
2.2.4 Outlook

Currently studies are being carried out to prepare the test facilities for the future. Topics are acceptance testing for VULCAIN and VINCI engines driven by cost reduction, new engine developments like Prometheus powered by methane; new propellants to replace hydrazine in satellite engines; applied research on and further developments of existing rocket propulsion systems. The test facilities will need to be more flexible in design and operation. To test different engines on one test position with different propellants like liquid hydrogen and methane is one of the challenges.

2.3 Operation of Test Facilities

2.3.1 Responsibilities of the Department of Test Facilities

The responsibilities of the department of test facilities are:

− Overall management of the respective facilities
− Their operation
− Their maintenance
− Their modification
− Their safety assurance
− Identification and correction of problems, identification of preventive measures.

2.3.2 Organization of Test Facilities Department

The Test Facilities Department is organized into three main groups:

− 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 P3.0 as well as the P3.2 thrust chamber test facility
− One group operates the supply facilities; the team members are specialized craftsmen qualified to work at the different facilities.

Some specific topics are handled outside these three groups. This concerns for example:

− Management of the renewals and upgrades of the facilities
− Controlling for specific test facility projects
− Project assistance.

Although it is not possible to operate facilities in parallel with the current team size, 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 are being tested for different users.

The two biggest facilities P4.1 and P5 can be operated simultaneously, albeit with an impact on flexibility and test cadence.

The status of the test facilities changes and the corresponding organisational aspects of this are challenging. The lead time required to start up a facility and partially switch from one bench to another, e.g. from operation of the facility P5 to the operation of the facility P4.1 is normally within one month so that the teams operating the facilities always need to be extremely flexible.

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

2.3.2.1 Test Preparation

Usually the campaign starts with the manufacturer and bench user delivering the test specimen. Either the manufacturer performs all activities on the test specimen himself or these activities are delegated to DLR personnel. This takes place e.g. in the case of Vinci or Vulcain type engines where DLR takes on the responsibility for all handling and installation activities on the engine. The transfer of all necessary information about the test specimen takes place during a special 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 preparations for the first hot run start which take place at different levels and areas and usually include the following steps:

− Connection of all test facility mechanical interfaces with the test specimen and verification
whether the connections are working properly (e.g. performance of seal checks)

- Connection of all test facility electrical interfaces to the test specimen and verification that the connection is alright (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 system including conditioner, filter setting and calibration of sensors.

- Study of the test documentation delivered by the user (test request, measurement request, request for activities on the test specimen) and in case something is unclear, liaison with the user.

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

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

- Programming and verification of media flow regulations on the MCC system as requested by the user and as per 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 check of recooling activities as regards the cooling water supply system.

- Verification of positive 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 behavior (NCR treatment).

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

- Documentation of all activities.

Figure 2.14: Transport of Vulcain 2 engine from M29 to P5

Work at the test facility is carried out 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 procedure lists the work sequences, stipulates which parts should be used and specifies individual steps.

There are written procedures not only for the engine, but for all activities at the test facility in order to ensure correct performance and to prevent mistakes. Each activity performed during preparation for the test is in writing in a plan, in the specimen logbooks as well as in associated documents, including, for example, a record of the configuration and setting of all bench systems or of 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 test clearance can be given. Planning meetings are held every week to coordinate the work of the various groups and to avoid clashes and stoppages.

Irregularities or faults in hardware and software are documented. A standard procedure (NCR - Non-Conformance Report) is available for every staff member to immediately record any non-conformance in writing. The Quality Department registers and manages these NCR. Every documented error must be eliminated or accepted before the test. Elimination measures are defined by the user's representative and the DLR test leader. An NCR is either solved or
accepted as is 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. Engine inspections are repeated before every test and the control sequences are re-defined and checked for every test depending on variations in their objectives.

### 2.3.2.2 Test Performance

The guidelines for the performance of the hot run itself can be found in the so-called chronology for the test. This document describes all steps necessary in order to prepare the test facility and test specimen on the test day to ensure the safety aspects and success of the test.

Operation of the test facility systems starts up successively on the basis of check-lists and procedures. The test team organization for each facility is handled by the test leader for each separate test. The test leader holds a daily planning meeting with his team to ensure an effective flow of communication and information. Other dedicated meetings of team members are organized if necessary. The test leader also maintains liaison with other departments such as Quality Assurance or Site Safety and the fire brigade and 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 only person during a test sequence who can decide on whether a test continues or is halted or stopped based on the information provided to him by his team.

The test leader chooses the team which performs the actual hot run test and each member has a designated and clearly defined role during the preparation phase and the actual test. This is important in order to prevent any misunderstandings and errors occurring.

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 the activities need to be effectively coordinated.

### 2.3.2.3 Test Post-Processing

After the test the bench data is evaluated by the DLR test facilities team while the manufacturer of the test specimen evaluates the test specimen data himself. Anomaly reports (NCR) are issued if anything unexpected has happened regarding the specimen or test bench. To optimize the performance during the next test, all anomalies are treated (solved or accepted with justification) before the next test.

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

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

### 2.3.3 Maintenance of Facilities

Maintenance is the main issue in order to keep the facilities operational over a long period of time and maintenance plans exist for each facility. They are reviewed periodically and updated if facilities have been modified. Maintenance is carried out by the same team which is also responsible for the operation of the facility.

#### 2.3.3.1 Maintenance Philosophy

Maintenance includes all technical, managerial and administrative activities, which are performed in order to guarantee the nominal status of the test facilities with respect to their technical installations and the related support systems.

The technical installations of the test and supply facilities basically comprise of:

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

As regards test and maintenance activities the status of the benches and supply facilities is always at one of a variety of different stages, i.e. operational, active waking, cocooning or stopped:

- **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 to be implemented in order to achieve its operational status in about one month time, maintenance is reduced due to the absence of test activities;
− or Cocooning ("dormant"): maintenance is reduced to a minimum, but still means that the facility can reach operational status after a few months of refurbishment and at a higher price than from active waking;

− or Stopped ("à l’arrêt"): the facility is unavailable; in this state a test bench cannot be used for tests unless a complete refurbishment phase is carried out to regain operational status.

− or Run down / Run up: the transition or reconfiguration phase from operational to a reduced (basic) maintenance status is called run down, the transition or reconfiguration phase from a reduced (basic) maintenance to operational status is called run up.

A test campaign is sometimes interrupted by a yearly maintenance period with a delay of no longer than 6 weeks if main systems (e.g. measurement and control systems) have to undergo maintenance. During the annual maintenance period the facility becomes non-operational, meaning no activities for engine testing can be carried out.

If a facility is not being used between two test campaigns, reduced maintenance can be performed. Reduced maintenance, also called “basic maintenance”, covers all activities for maintaining the facility in a pre-defined status (e.g. active, waking or cocooning).

There are different kinds of maintenance work required for the upkeep and restoration during the lifecycle of technical equipment:

− preventative maintenance (i.e. undertaken regularly according to predefined intervals), subdivided into 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 the normal working process).

− corrective maintenance, subdivided into palliative and curative corrective maintenance. This type of maintenance could mean equipment is being repaired or replaced and is conducted to get equipment back into working order.

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

− 1st level maintenance covers simple actions, which are necessary to maintain the normal running of the system such as daily greasing, purging of filter elements or inspection rounds to verify status and proper functioning

− 2nd level maintenance covers easy-to-perform actions which require simple procedures and/or utilization 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 and is carried out by qualified technicians

− 4th level maintenance covers operations which require a working knowledge of a particular technique/technology, for example vibration analysis, replacement of a compressor check valve or servicing of a pump in a specialized workshop

− 5th level maintenance is defined as the renovation or reconstruction carried out by the manufacturer or a specialist company.

The tasks of staff members responsible for maintenance include the:

− management of objectives, best strategy

− team organization

− choice between preventive vs. corrective maintenance, systematic or conditional maintenance

− coordination and synchronization of all relevant maintenance activities

− detailed planning

− decision as regards in-house or subcontracted external maintenance

− guarantee of compliance with quality assurance

− NCR analysis and consequences

− application of the technical standards and rules

− internal and external reporting

− implementation of lessons learned.

Each system or part of a facility consists of a certain number of subsystems and/or elements for which maintenance actions are defined. These actions take into account the manufacturer’s recommendations.
and feedback from the operational team and constitute a part of the maintenance activities. All maintenance activities are supported by an internal DLR Software maintenance tool developed by the Department of Test Facilities. The software package provides assistance in the following cases:

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

The software also serves as a database of knowledge 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.

### 2.3.3.2 Maintenance Plans and Reports

All maintenance plans and periodical reports of the facilities conform to DIN norms, VDI principles, special rules [e.g. AD notice sheets: regulations regarding pressure cylinders (AD – Arbeitsgemeinschaft Druckbehälter); UVV (Unfallverhütungsvorschriften): installations to be examined], instructions by the manufacturer as well as on 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 processes.

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

In each section catalogue sheets of maintenance work for each subsystem are defined with an identification number as well as the description of the type of activity and at what regular interval the work should be carried out.

The various types of maintenance work are performed during the course of the year, and as a minimum requirement the activities regarding 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 tasks appear in the schedules as times of reference; the real-time maintenance activities are adjusted to fit in with the actual activities at the test facility.

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

As mentioned before, the Department of Test Facilities has developed a software tool which covers all maintenance activities for the respective facilities. Specialists manage this software tool and keep it up to date. It is programmed to automatically create the maintenance report.

### 2.3.3.3 Spare Parts and Supplies

In addition to special equipment and tools, spare parts and consumables are items which are required to carry out maintenance.

The optimum provision of spare parts is a prerequisite for all types of tasks involving maintenance such as inspections, preventive maintenance and repairs. Except in the case of preventive activities spare parts for maintenance tasks are usually required at random intervals. Therefore an important aspect of the ability to carry out maintenance at the right time is coordinating the demand for spare parts and their supply.

Spare parts management and a well-organized storeroom are key issues which support effective maintenance planning and scheduling and improve equipment reliability.

The Department of Test Facilities has developed a software tool called “LVP” (Lagerverwaltungsprogramm) for managing and organizing spare parts and consumables. The following tasks are carried out using this tool:
- database for spare parts and consumables including a definition of the minimum quantity required and in stock and including an automatic reminder
- spare parts and consumables planning activities
- managing tasks such as assistance with the ordering process
- management of assets (parts, tools, equipment inventories)
- database of spare parts and consumables history log
- database on serial numbered parts
- support of maintenance and repair documentation and best practices
- reference for warranty/guarantee documents.

Therefore all the relevant parties have a complete insight into the availability of the required material. The material withdrawals are documented and form the basis for planning of material availability controlled by usage. This results in optimizing maximum availability/minimum stock levels of spare parts and consumables.

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

Common supplies such as oil, grease, etc. for the test facilities are standardized in order to limit procurement and storage costs and to minimize the risk of expiry dates being exceeded.

2.3.3.4 Renewals / Upgrades

The test facilities and relevant support systems need to operate efficiently over a long period of time. Meanwhile not only technical know-how improves, also legal requirements may have changed. The so-called renewals and upgrades program for the facilities is in place in order to provide the Department of Test Facilities with the necessary information in this case.

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

A system, subsystem or piece of equipment needs to be renewed when:

- maintenance of the item is no longer possible because it is obsolete or its main components are no longer available.
- the item can no longer be serviced due to the fact that the sole supplier has gone out of business.
- the operating and maintenance costs have risen to such an extent (e.g., due to necessary repairs) that its use is no longer cost-effective.

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 evaluating MTBF (mean time before failure) and determining how critical the equipment is
- information from suppliers and manufacturers
- results of internal and external audits
- results from dealing with NCR's and from the performance of maintenance activities
- information about the life time and use of the equipment, i.e., life cycle of the equipment
- evaluation of costs and cost factors.

The selection method for defining and prioritizing 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 impact on testing activities
- the total costs for the new equipment
- the equipment's down-time over the last year
- the legal requirements regarding due date and the urgency of carrying out an upgrade
- the time needed to design, manufacture, install and get approval for new equipment.

2.3.4 Modification of 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 development of a new test facility is managed by the Department of Engineering at DLR Lampoldshausen during the course of the standard design phases up until the Critical Design Review. Thereafter the Engineering Department gradually hands over the responsibility for setting up and commissioning the new facility to the internal Test Facilities Department at DLR Lampoldshausen.

Their one main goal is to work together with the team which will operate the test facility in future to preserve and use the know-how and experience for the operational phase of the facility.

When the new test facility is finished and the commissioning is completed, then operation of the facility begins. During operation modifications and adaptations to the facility also have to be carried out mainly because either test objectives or the specimen hardware have been altered from the user side. DLR Lampoldshausen therefore has a configuration and modification management system. The initial configuration of the facility is fixed by the as-built and commissioning status established and documented in a so-called CRE or ‘Acceptance Review’ meeting.

Modifications to the facilities are defined and carried out according to a so-called DMI process (DMI = Demande Modification Immédiatement) which ensures that each modification of a facility is planned, checked, performed and documented.

Modifications can be identified according to a numbering scheme and they are documented in specific form sheets. They may vary from being very minor up to modifications in the functionality of the test facility. Each modification is discussed and checked by a committee where decisions about financing, technical feasibility and realization of the modification are made. The committee consists usually of representatives from DLR as bench operator and the respective bench user and ESA as the owner of the asset. Implementing the DMI is the responsibility of the Test Facilities Department.

Each DMI has to be documented in a certain way and the acceptance is subject to a so-called PV (Process Verbal, a specific protocol or acceptance).

In this DMI process one step also entails updating the as-built and commissioning status.

2.3.5 Training of Personnel

The above-mentioned special requirements as well as general fluctuations in staff make it necessary for special training or preparation as regards their tasks in the test team. Each new team member receives an appropriate and customized training matrix. In addition to the in-house DLR training program experts are contracted to teach the necessary knowledge or methods. This comes into effect also in connection with specific equipment, e.g. hygrometry measurements, mass spectrometer operation or the use of forklifts or cranes.

Training to a certain degree is also necessary for all personnel as regards the special safety aspects on-site. Hence, regular sessions are held particularly as regards the use and handling of dangerous products such as the propellants stored in large quantities at the test facilities.

Furthermore the Department of Test Facilities has developed a program of courses specifically to train its craftsmen (mechanical and electrical). This internal program was certified in August 2001 by the authorities and, if successfully completed by the craftsman, can result 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 the hardware they handle is complex, expensive and unique. Mistakes made in handling can lead to high maintenance and campaign performance costs.

These courses are an integral part of a step-by-step training program to be held by internal specialists due to the uniqueness of the facilities, test specimen and processes.

The training program includes four modules. After each module the trainees have to take a written test and if successful are presented with a certificate. It takes four years to complete the training course and one module per year is possible. The level of performance during training is checked on a regular basis by means of certification as part of DLR Lampoldshausen Integrated Management System. In addition to such standard training there are also team training sessions held for the respective test bench teams in order to improve operational procedures, communication and team-work which are essential aspects in performing safe and successful test campaigns.
2.3.6 Safety of Facilities

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

Storable propellants are carcinogenic and harmful pollutants and have to be treated accordingly.

Specific safety measures which are always in effect include the following:

- Access to the facilities is only permitted for trained personnel. Visitors or untrained personnel have to be in the company of trained personnel at all times. Access permission to the facilities can only be granted by the Department of Test Facilities. Specific instructions and training courses are applicable for external personnel which have to perform activities on the test facilities.

- Specific safety measures are in place, for example remote sensors for propellant detection are installed at the facilities as standard features, they undergo checks and their standard is maintained on a regular basis.

- Activities as regards the handling of storable propellants where personnel have to be present is only allowed if they wear special personal protective gear which is also regularly checked, maintained and upgraded.

- For specific procedures such as e.g. tanking operations certain additional restrictions apply and have to be followed and documented.

- Communication between different test team members during specific 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. The integrated alarm system ensures that problems can be handled 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 in the case of a malfunction. An extensive video system at each test facility continuously monitors the current situation.

- The staff of the DLR Department of Test Facilities takes part in regular training exercises as regards the aforementioned topics.

The high density of energy generated when an engine is running is a potential danger in itself. The possibility of a fault causing considerable damage to that engine and its surroundings cannot be completely ruled out.

It is therefore strictly forbidden for anyone to be in the vicinity of a running engine. Procedures are organized in such a way that the test facility is cleared completely of personnel before activation in preparation for a hot firing test occurs. 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 initial access to the facility after the test, global leak detection is carried out along the supply lines and around the engine itself and a small group of staff carries out a visual inspection.

2.4 Test Facilities and Supporting Facilities

2.4.1 Supply Facilities Operation

The supply facilities, i.e. the cryogenic and gaseous supply as well as the cooling water supply facilities - are operated in close co-operation with the external company Air Liquide Deutschland ALD. The DLR Department of Test Facilities has overall responsibility and is in charge of the site. In order to coordinate supply operations with overall testing activities as well as modification and maintenance actions on the supply facilities themselves, there is a specific officer (as well as a deputy) within the Department of Test Facilities who acts as the direct interface between ALD and the Department.

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

2.4.2 T23, T58, Cryogenic Supply

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

The T58 depot not only supplies the P5 test facility with liquid hydrogen but also P4.1 and in future the P5.2 European Upper Stage Test Facility. T23 supplies P5 and P5.2 with liquid oxygen. P4.1 has its own oxygen supply located at the P4 steam generator plant.

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

Including the test facility equipment 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.

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 once. An amount of approximately 200 m³ liquid hydrogen can be delivered in one day.

The hydrogen from the storage tank runs during the preparation phases between the tests through pipes (approx. 350 m to P5 and approx. 500 m to P4.1) to the run tanks at the respective facility.

As in the case of the hydrogen depot the liquid oxygen depot consists of the following elements:

- Vacuum-insulated storage tank with 210 m³ capacity, a storage temperature of 90 K
- Two connections for tank vehicles
- Pressurisation system
- Transfer pipe 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 transfer pipe to the run tank of the P5 test facility. The transfer pipe is of the same design as the hydrogen pipe to the P5 with a transfer rate of up to 40 m³ per hour. For the P5.2 supply a T-junction is built into this LOX transfer pipe so that the Upper Stage filling with LOX can be performed.

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

Both depots have been in operation since 1990. Over this period the facilities have been supplied with around 108,200,000 Nm³ (normed cubic meters) liquid hydrogen and around 37,200,000 Nm³ liquid oxygen.
More than 7,800 trailers with liquid hydrogen and liquid oxygen have been unloaded during this time: an impressive illustration of the safe handling procedures of these installations.

2.4.3 Conventional Propellant Depots

Depot T16

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

Nowadays the depot is used as a backup storage area in case of either problems with the facilities' own supply systems or a 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 vapor or dilute any leaks. The resulting acid water is transferred to the decontamination system.

Depot T18

The T18 fuel depot 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 freely in case of a leak.

Depot T21

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

Depot T13

The T13 depot for solid fuels was constructed 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 blockhouse facility which was built especially for this kind of material and certified accordingly by the authorities.

There is an adjoining air-conditioning chamber which is adjustable to cater for a broad range of temperature and humidity requirements for the storage and testing 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 authorized companies are allowed to transport and deliver the igniters.

2.4.4 Gaseous Supply

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

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

Figure 2.17: Control Building for Supply Facilities G56

Supply of Gaseous Hydrogen

The D57 hydrogen compressor station 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:

- P5 test facility: five pressure tanks with a capacity of 8 m³ each for max. 320 bar
- P4.1 test facility P4.1: five pressure tanks with a capacity of 8 m³ each for max. 320 bar
- P3.2 test facility: 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
- P8 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 pressure for the compressors is in the range of between 2 and 6 bar.

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 end users:

- 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 end users scattered across the site (e.g. laboratories and workshops).

The original system for generating nitrogen gas went into operation together with the P5 test facility. In 2010 after more than 20 years of operation the system was renewed under the terms of an ESA contract.

The D22 system supplies the 200 bar network via four pumps. The production station 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.

For the GN₂ supply of the new P5.2 European Upper Stage Test Facility a new production facility, the D57A, was installed and started operation in 2016.

The D57A consists of the following main sub-systems:

- 5-6 LN₂ storage tanks (60 m³ geometric capacity each, the actual number of tanks depends on the final test duration required)
- Evaporator trains for the MP and LP system each including heating systems with fuel storages
- Two LN2 pumps (MP=78 bar and LP=10 bar) with variable speed drive
- GN2 booster panel for LN2 storage pressurization
- Filling station for LN2 storages by trailer.
Supply of Gaseous Helium

A membrane compressor (230 bar, 175 m³ per hour) supplies helium gas to P₅, P₄.₁ and P₄.₂. Prior to compression the helium is taken from a bottle transport delivery vehicle (2,500 m³, 200 bar) which is regularly exchanged.

2.4.5 Cooling Water Supply

Large test facilities such as the P₄.₁ require a supply of over 4,200 liters per second of cooling water during testing. Three reservoirs supply the water to meet this huge demand.

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

− a tank with a capacity of 1,000 m³ at 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 P₃ and P₄ test facilities with a capacity of 1,400 m³.

It then became necessary to enlarge the water supply system at the start of the Ariane 5 project when the P₅ facility was built and the P₄.₂ test facility was modified. 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 the P₅ test facility
− replacement of the water cooling system for the existing N₃₃ tank so that the water which was warmed up in the P₄.₂ test facility can again be cooled down to temperatures of around 5°C.

When the P₄.₁ test facility P₄.₁ was built 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 N₆₃A water tank 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 P₄ test facility 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 in the tanks but in N₆₃A (new) in particular 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 special water pumps for specific cooling applications.

The remaining cooling water in the concrete basin of the P5 test facility 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.

In order to safeguard the cooling water supply, to reduce implementation of necessary treatment and costs a new supply from Lake Constance Water is currently under construction. There will be a connection made to the city of Möckmühl which has a Lake Constance Water Supply. The benefit in using the Lake Constance water supply is that the quality of this water is guaranteed of a high standard especially as regards the low level of hardness.

2.4.6 Decontamination Plant N39

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

When handling these substances it is unavoidable that remnants find their way into the waste water stream and therefore it is important that special measures are in place to deal with this. All waste water from test facilities P1, P2, P4.2 and from tank depots T16, T18, T19, T20 and T21 flows to the N39 decontamination plant. All precipitation water in the vicinity of these tank depots and test facilities is also considered to be possibly contaminated.

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 refurbished in 1998 in order to reduce operational and maintenance costs and to maintain a state-of-the-art level of technology.

It was decided to install a system using catalytic water oxidation with hydrogen peroxide and ultraviolet light. As part of 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 procedure are that the water treated is of a high quality, the failure rate is low, due to basic reactor technology, the supervision requirements by personnel are low and the potential for expanding the system is good.

![Scheme of functionality of N39](image)

Although the decontamination plant is automated, samples of the water discharged from the plant are taken daily for testing in order to ensure that no undesirable substances are discharged with the waste water and also as a regular check that the plant is functioning efficiently. Unannounced sampling is also conducted at irregular intervals by the responsible authorities to check that they comply with the mandatory requirements.

SOWARLA

The regular process of decontamination as described above needs certain amounts of energy and chemical substances. For this reason a demonstration plant for the purification of water using solar light and photocatalysts was developed. This project was created following the initiative of the Technology Transfer Center 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 a new receiver-reactor technology. This technology is based on patented solar modules with robust glass pipes with a very high degree of transparency.

The polluted water is mixed with photo-catalysts and oxidants, the receiver is charged and is 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.

The characteristics of the demonstration plant are as follows:

− Solar receiver area of 240 m²
− Saving of electrical energy and of chemicals
− Purification of 4,500 liters per charge
− Modular solar receiver
− Robust design of the plant
− Efficient monitoring with automated operation
− The catalyst is reusable.

This demonstration plant and the conventional treatment plant with the N39 UV-Oxidation-Facility operate in parallel.

Figure 2.23: SOWARLA demonstration plant

Figure 2.24: Scheme of functionality of SOWARLA

2.4.7 Workshops, Assembly Buildings and Spare Parts Storage

The Test Facilities Department maintains several workshops located both at the separate test bench sites and otherwise elsewhere. These are necessary particularly for maintenance work, minor repairs and modifications. Major work is usually contracted out to external companies.

Figure 2.25: Assembly Buildings M9 and M29

Two assembly buildings are available, M9 and M29. The M29 building was specially set up for work on the Vulcain engine and also accommodates the extensive stock of spare parts for the ESA test facilities and supply systems. The M9 building was used for work on the Viking engine and is used today also 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.
2.5 Test Facility P1.0 and Control Building M6

2.5.1 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 found under sea-level conditions. In addition the engine has a higher thrust and power output while operating in a 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 P1.5 high-altitude test facility was built at the P1 test facility complex under the ELDO program. It was the first facility of its kind at DLR Lampoldshausen and was modified in 1978/79 to handle the development of the propulsion system for the Jupiter probe Galileo.

As technology evolved a new high-altitude test facility was required. A decision was therefore made to develop P1.0 into such a high altitude facility to 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. Testing can take about two hours with an ambient pressure within the vacuum chamber below 2 mbar.

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

2.5.2 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. Variations 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 deactivated, the auxiliary nozzle is shut down. Purging with a small amount of nitrogen reduces back-flow into the altitude chamber.
- Once the shut-off valve has been closed the steam generators are switched off. The vacuum can be maintained for a while longer using the mechanical pumps.

The steam generator which is necessary to power the high altitude simulation system of the P1.0 produces 10 kg of steam per second with a temperature of around 200°C and a pressure of about 20 bar. The steam generator is powered by alcohol and liquid oxygen as propellants and was developed by the Institute’s own Department of Engineering.

The steam is divided between different sections of the high altitude simulation system according to the following list:

<table>
<thead>
<tr>
<th>Ejector Stage</th>
<th>Steam Flow Rate</th>
<th>Suction Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Ejector Stage</td>
<td>≈ 1.6 kg/s</td>
<td>≈ 60 mbar</td>
</tr>
<tr>
<td>2nd Ejector Stage</td>
<td>≈ 8 kg/s</td>
<td>≈ 280 mbar</td>
</tr>
<tr>
<td>Auxiliary Nozzle</td>
<td>≈ 0.4 kg/s</td>
<td>≈ 1 mbar</td>
</tr>
</tbody>
</table>
The volume of the vacuum chamber is about 4.5 m³ and the vacuum possible is around $10^{-5}$ mbar.

Due to the hot exhaust gases coming from the apogee engine, the high altitude simulation system needs to be cooled. The hot gas cooler has a cooling capacity of 1.400 kW and has to sustain an inlet temperature of about 1.280°C. Its outlet temperature 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 mainly Monomethylhydrazine MMH and Dinitrogen tetroxide N₂O₄. The propellant tanks at P1.0 have a capacity of 1.000 L for MMH and 1.000 L for N₂O₄. Additional tank capacities of 150 L exist for both propellants and the temperature is variable.

In 2015 tests for engines using H₂O₂ as propellants took place. A special separate supply was temporarily made available. An appropriate risk analysis was carried out and specific safety measures were put into place including extensive training of the personnel handling the H₂O₂. The tests went very well and demonstrated how flexible the test facility and personnel are and how quickly they can adapt and react to new situations.

In 2016 monopropellant tests were also carried out very successfully.

P1.0 has an infrared camera and a pyrometer which measure the temperature of the engine without direct contact.

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 and back-end computer. The back-end system is used during test preparation and for evaluating the test runs. While the test is running it shows the hot run parameters and the 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 taking analogue measurements of which 8 can run at frequencies of up to 100 kHz. 504 further channels are available for digital commands.
2.5.3 Utilization and Users

Apart from apogee engines for communication satellites, engines for different research probes have also been tested at P1.0. In addition, for example, the potential engines for Ariane’s upper stage control system have been tested under simulated high altitude conditions.

Also tests of the control thrusters for the ATV Modules have been carried out at P1.0.

The main user of P1.0 is Airbus Safran Launchers (ASL) which uses the facility on a regular basis for the qualification and commissioning of its 400 N Apogee thrusters and also for specific developing of engines with a thrust range between 200 N and 600 N.

The Norwegian company Nammo, working under an ESA contract, has put in an order for H₂ O₂ thrusters high altitude simulation testing.

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

In addition to the facilities described in the previous chapters DLR has other test facilities on-site which are used by ASL in the general context of utilization contracts for ASL’s own development work. These are:

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

Test facility P2 is the largest of the benches listed above and was one of the first to be constructed on the site at Lampoldshausen.

It has a supply tower which accommodates the subsystems necessary for carrying out tests and 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 of sight for monitoring P2.

The small test facilities P1.2 to P1.6 are part of the P1 test facility complex. Their control rooms are also located in the M6 building which stands parallel to P1. Here smaller engines for use in satellites are developed.

All the facilities mentioned in this chapter use storable propellants.

2.7 Test Facility P3.2 and Control Building M7

In addition to the facilities described in the previous chapters DLR has other test facilities on-site which

2.7.1 Background

The P3 test facility was originally built in 1963 under the ELDO program and was used for testing the third stage engine for the Europa launcher. The P3 test facility is still in operation today, was renamed P3.1 and can be modified to satisfy future requirements.
The original high altitude test facility has been dismantled.

The P3.2 test facility has been built between 1986 and 1988 next to the old P3 test facility building, (nowadays P3.1). Its purpose was for the development of the thrust chamber of the Vulcain engine by EADS Astrium.

In 2003 the P3.2 test facility was adapted to cater for the development of the Vinci engine thrust chamber by EADS Astrium.

In 2015 the facility was again modified in order to be able to test a demonstration thrust chamber using LOX-Methane as propellants. This project was a joint effort carried out by DLR and ASL.

The next adjustment is already in progress in order to test the ETID (Expander Technology Integrated Demonstrator) Thrust Chamber in 2017/2018 within a ESA FLPP contract, with ASL as prime contractor and DLR as sub-contractor.

The CDR for this modification was successfully performed in October 2016 and the procurement and modification process started.

The testing activities for ETID on P3 will begin in autumn 2017.

2.7.2 Characteristics of the Facility

P3.2 was originally built to provide 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 almost 200 bar for operation at more than 100 T thrust lasting for up to about 20 seconds.

The test cell of P3.2 is erected behind a solid concrete wall to protect the supply systems. It takes in 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 is able to simulate vacuum conditions for the ignition and start-up of the thrust chamber as installed. The vacuum system is covered 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 maintains the conditions in the vacuum chamber at 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 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. The volume and pressure are 4,5 m³ at 350 bar for the oxygen tank and 12 m³ at 400 bar for the hydrogen tank. The feed lines to the thrust chamber in the test cell are vacuum-insulated and can also handle 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 adjustment is computer-controlled. The pressurising gas comes from high-pressure bottles each of which holds 15 m³ and can be charged up to 800 bar from the central gas supply.

As regards the methane supply the existing LH2 tank was used and also the supply lines installed for LH2 were used as is for supplying methane. The following summarizes the main modifications which have been carried out:

- Integration of a CH4 vaporizer in the storage tank area to produce CH4 gas
- Modification of y-section B14A/B GH2 high pressure bottles to separate B14A bottle from B14B bottle
- B14B high pressure bottle then used for CH4 gas supply
- Several mechanical adjustments in connection with, e.g. feed lines, TC lines etc.
- No major critical mechanical modification was identified
- The gas detection system was partly modified and extended to detect CH4 gas
- The operating licence/permit was extended to include the use of CH4 as a new propellant
- Several TÜV approvals were necessary as well as a verification of the compatibility of the materials used at the test facility so that operation permits could be extended
- LH2 storage tank B12, run tank B10 and LH2 feed lines were used for CH4 as is without major changes or modifications
- Calibration of measurements for the use of CH4
2.7.3 Utilization and Users

P3.2 is currently mainly being used to test thrust chambers within the guidelines of ESA programs (Vinci, ETID). ASL is using P3.2 within the terms of such an ESA contract as main customer. At P3 the successful testing of a LOX-Methane Thrust Chamber developed by ASL took place in agreement with ESA as part of a cooperation agreement between ASL and DLR.

P3.2 is a very important resource as it is the only test facility for thrust chambers in Europe.

2.8 P4 Test Facility

2.8.1 Background

The P4 test facility was built 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 such pressure conditions.

The facility had to be adapted in 1974 for the Ariane development program and P4.2 was subsequently used to test the Viking engine, i.e. the propulsion system for the first and second stage of Ariane 1 to 4. Between 1976 and 1979 the P4.1 test facility 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 P4.2 test facility was used for altitude tests of the Viking engine until 1981. From 1981 to 1984 more sea-level testing on the engine was carried out. The third phase of test facility P4 began with the start of the Ariane 5 launcher program. 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. P4.2 was therefore modified in 1991. The high-altitude facility has to maintain a low ambient pressure of just a few millibar during the whole test phase and had to be modified and adjusted to fulfill the new requirements.

A refurbishment of P4 was then carried out in the middle of the 1990s when a new MCC system, designed and manufactured by the French company Nexeya, was installed. Additionally a new building for the steam generator plant was set up.

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

At the end of the 1990s ESA came to a decision regarding the further development of the Ariane 5 including a new cryogenic upper stage engine, the so-called Vinci engine. Heading this engine system development program was the French company Snecma (today Airbus Safran Launchers).

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

Since 2005 this facility has been performing 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. This changed in 2009 and afterwards the tests have been carried out as part of the ESA A5ME (Ariane 5 Midlife Evolution) program. Following the decision during the ESA ministerial conference in 2014 that Europe will build a new Ariane 6 launcher instead of finalizing the A5ME program the test facility again underwent some modifications to conform with Ariane 6’s requirements. 2016 marked the beginning of development and qualification testing of the Vinci engine for the Ariane 6 Upper Stage. This will carry on until 2018.

### 2.8.2 Layout of the Test Facility P4

Nowadays the P4 test facility consists of three different facilities: the P4.1, the P4.2 and the P4DE steam generation plant 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 hillside location means that the rear of the building is 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 pressurized air supply to prevent infiltration by any gas or vapor.

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 MB (see chapter 2.1.2).

### 2.8.3 Test Facility P4.1

Construction of the test facility began in 2000 and the first hot firing test was performed in 2005. Up until the middle of 2008 tests on the two Vinci engine demonstrators were a great success with a total of five campaigns involving 37 individual tests and including re-ignition experiments. The development of an Ariane 5 upper stage with a Vinci engine suitable for commercial use began in 2010. During four campaigns with three Vinci engine development models a total of 54 individual tests were performed. Numerous important milestones were achieved during work on the Vinci engine. The first hot fire testing of a complete extendable new nozzle, which is made of a 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.

In 2014 after the decision was made at the ESA ministerial conference to cancel the A5ME program, work on refining the Vinci engine continues for the benefit of Ariane 6 with P4.1 playing a vital and necessary role in this development.

One campaign was successfully performed in 2016 with very challenging objectives, e.g. of getting the Vinci engine closer to flight. More than 100 Vinci engine tests have now been performed. With one additional development campaign ahead, Vinci nears
its qualification phase which is planned to begin in 2017.

The Vinci engine is being tested by DLR under a contract with the European Consortium Airbus Safran Launchers.

2.8.3.1 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 and 6 respectively. 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 2.15 m 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 6 will be able to release several payloads into different orbits. Accordingly, the P4.1 facility was therefore designed to test 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 2.33: 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 crucial 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) gets rid of 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 and in addition parts of the altitude simulation system are '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 can handle 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 on hand, and there is a refrigeration system for cooling it down to around 7°C.

The engine to be tested is mounted inside the vacuum chamber of the P4.1 and the propellant and gaseous supply lines are fitted accordingly. 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 a supersonic velocity and re-compresses 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 module of this kind in Europe.

In the condenser the entering exhaust gases are sprayed with more than 4,000 liters of cooling water per second in order to condense the water contingent contained within.

The condenser had to be put together on the construction site in Lampoldshausen as it would have been too big for transport via the public road network. 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. The following vacuum pumps are available for this task:

- 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 P4.1 test facility is supplied with cooling water from the three central cooling water towers through two pipes.

For a test run on P4.1 the complete water reservoir of around 6000 m³ has to be cooled through a water recooling 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 1,300 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 available. Two additional small buffer tanks, one for each propellant, are also on hand to simulate flight conditions during operational stages such as start-up 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 P4.1 vacuum chamber. This is achieved by pressurizing the liquid hydrogen tanks with gaseous hydrogen and the liquid oxygen tanks with gaseous nitrogen.
The liquid propellant tanks at P4.1 are filled during the test preparation phase, i.e. the liquid hydrogen is transferred from the T58 central liquid hydrogen storage area and the liquid oxygen is conveyed via a specific vacuum-insulated pipe 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 of up to 320 bar and the associated mass flows up to several kilograms per second.

To achieve this specific gaseous supply systems are installed in the P4.1 test facility. The available media are mainly for fulfilling 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 pipes which were in contact with propellants during the test
- post-test purging and warming up of all pipes which were in contact with propellants during the test
- venting and diluting of leakages if necessary
- safety pressurisation and purging of pipes and volumes with nitrogen or helium
- use of helium as a sealing medium in the oxygen turbo pump of the engine
- supply of propane burners in order to systematically burn all gaseous hydrogen coming from the bench pipes
- supply of the command pressure circuit of the bench which uses gaseous nitrogen in order to activate valves controlled pneumatically.

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 achieved via optical cabling.

At the P4.1 test facility 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 1400 digital signals and various 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 firing test, calculations and regulation can be performed throughout the whole duration.

At the P4.1 test facility more than 20 GB of data is acquired and stored in the course of a single test of a maximum of 700 s duration.

2.8.3.2 Utilization and Users
P4.1 is currently designated for developing the Vinci upper stage engine within the terms of the ESA Ariane 6 program. Heading the Vinci engine development program is the European Consortium Airbus Safran Launchers. The basic maintenance of the P4.1
is contracted by ESA LEAP directly to be carried out by DLR.

The Vinci development campaigns are scheduled to continue up to 2018 at P4.1.

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

P4.1 is the most modern and most high performing test facility available in Europe today. It is indispensable for 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.

2.8.4 Test Facility P4.2

Since P4.2 was refitted for engine stage configuration tests in 2001 it has been used for vacuum tests with hot run times between 0.7 seconds and 300 seconds. The AESTUS engine is being tested on P4.2 in its flight-stage configuration.

In order to handle the dangerous propellants safely a respiratory air supply (1 m³ at 200 bar) for supplying full protective suits is installed.

**Engine Propellant Supply**

The propellants used in this test facility are dinitrogen tetroxide (N₂O₄) and monomethyl hydrazine (MMH), which are toxic. After the combustion stops, the residual gas must be drained from the propellant tanks and all supply pipes before they can be opened. The recovered gases contain propellant vapors and are cleaned at P4.2. N₂O₄ is scrubbed with a sodium hydrogen solution. MMH vapor is condensed out in a cold trap.

The propellants are stored in stainless steel storage tanks each with a capacity of 25 m³ at a pressure of up to 5 bar and located in separate rooms on either side of the test facility. They are pumped into run tanks located above the high-altitude chamber before testing begins. The AESTUS engine uses two propellant tanks each with 1.5 m³ capacity and an operating pressure of up to 40 bar.

If any problems occur during a test run the propellants are drained back from the run tanks into the storage tanks. All activities at P4.2 involving propellants which are a risk to health are subject to strict safety precautions. Specific safety equipment is in use and safety training for the personnel is carried out on a regular basis.

**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 has a mechanical connection with the propellant pipes of the stage simulation tanks and the device measuring the thrust. It is also connected electrically to the measuring and control lines.

Before a test starts several vacuum pumps empty the altitude chamber and parts of the high-altitude facility: a water-ring pump as a preliminary unit reduces the pressure down as far as 100 mbar and two vacuum pump units can handle pressures in the low mbar range.

The exhaust jet from the engine flows vertically down into the supersonic diffuser containing 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 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 configuration of the P₄.₂ altitude simulation system (see Figure 2.36 below).

The system is similar to the P₄.₁ but less sophisticated.

Figure 2.36: Sectional view of the high altitude simulation facility P₄.₂

The P₄.₂ test facility is supplied with cooling water from the two cooling water towers N₃₃ and N₆₃ via a supply pipe with a diameter of 1 m.

The geodetic water pressure from the water tower is not enough to meet the demands of all applications, so there are water pumps to increase the pressure in particular to cool the supersonic diffuser. The cooling water from the P₄.₂ facility which is potentially contaminated is collected in a special underground water storage tank below the plant and treated in the N₃₉ decontamination facility (chapter 2.₄.₆).

MCC – System

The MCC – System of P₄.₂ is designed and functions in the same way as the P₄.₁ system but there are less channels available:

- LF data acquisition of up to 296 channels with a rate of up to 1000 Hz
- HF data acquisition of up to 48 channels with a rate of up to 50 kHz
- Command system for up to 928 digital input and 416 digital output signals and various command sequences, regulation routines and monitoring.

2.₈.₄.₂ Utilization and Users

The P₄.₂ test facility is currently in use for further development and flight acceptance testing of the AESTUS upper stage engine which is being designed, developed and built by Airbus Safran Launchers. P₄.₂ is the only facility available able to carry out hot fire tests on the AESTUS engine and even under vacuum conditions for long durations.

The P₄.₂ test facility currently carries out not only AESTUS ARTA/LEAP test campaigns but also the flight acceptance testing of each AESTUS engine before being integrated into the Ariane ₅ upper stage.
These engines have highest priority and are qualified for flight at the P4.2 test facility with a special test profile.

The facility is maintained and kept technically up to date via a direct ESA LEAP contract with DLR. At present P4.2 is the only test facility in Europe where large engines with more than 20 kN thrust capability using storable propellants both under vacuum and sea level conditions can be tested. P4.2 is therefore strategically important for the European space flight program and it is vital that its competency for performing this kind of testing is maintained.

2.9 Test Facility P6.1

2.9.1 Background

The P6 test facility was built in the mid-1960s in order to carry out national research programs as regards high energy propellants.

Work on P6 was finalized in 1966 with the completion of two test cells – P6.1 and P6.2.

Tests with combinations of liquid hydrogen and fluorine were performed at the P6.1. Research into combustion driven HF and DF lasers was carried out at P6.2.

Later on steam generators using hydrogen and oxygen were developed here.

The P6.1 test facility is operated by the Department of Test Facilities as described in the following sections.

2.9.2 Characteristics of the Facility

Since 2006 P6.1 was designated as a Green Propellant Test Facility and can be operated 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, this test facility is less powerful than the P8. Nevertheless the size of P6.1 classifies it above that of a laboratory and for this reason only specially trained teams are allowed to operate it.

P6.1 offers favorable conditions for the application of optical diagnostics.

Test Specimen Propellant Supply

The system for liquid oxygen consists of one run tank which can be cooled down using a shell filled with liquid nitrogen.

The maximum pressure that can be achieved in the LOX system is 150 bar, and the maximum mass flow is 1 kg/s.

The fuel system can be used either with gaseous or liquid methane or with hydrogen. The run tank consists of three gas bottles.

The maximum pressure possible in the fuel system is 150 bar, the maximum mass flow is currently 250 grams per second for hydrogen and 500 grams/s for methane.

The liquid methane is produced in the fuel run tank, which is enclosed with a shell of liquid nitrogen in order to liquefy the fuel.

The feed lines are also equipped with jacket cooling systems.

During a test the mass flow to the test specimen is defined by a particular control valve setting and a closed loop algorithm.

MCC System

The MCC System for test facility P6.1 was designed and delivered by the German company Werum and uses the LabView software package.

128 LF measurement channels and 16 HF measurement channels are available.
2.9.3 Utilization and Users

The P6.1 test facility went into operation in 2009 and has been used to perform test campaigns for Airbus Safran Launchers and for DLR research projects. P6.1 is open to a wide range of users and rounds off the portfolio of testing capabilities at DLR Lampoldshausen.

2.10 Test Facility P8 and Control building D68

![Figure 2.38: Test Facility P8 during a hot run](image)

2.10.1 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 design of a European research and technology test facility on the basis of a Memorandum of Understanding between DLR, the French Space Agency CNES and the industrial companies SEP in France and DASA in Germany. This agreement was the first of its kind to succeed in securing joint financing of a test facility for use by different partners. The facility was planned, built and commissioned and is today operated by DLR on behalf of the various users. The first test was conducted in 1995 and since then it has been in operation over more than 1400 test days.

2.10.2 Characteristics of the Facility

The essential features of the P8 test facility can be summarized as follows:

- High availability rate (up to 100 test days per year) made possible through the construction of two identical test cells P8.1 and P8.2 to optimize specimen mounting procedures.
- Possibility of access for optical measurement from the two adjoined diagnostic rooms per test cell
- Usage of noise suppression systems to keep in line with the required noise emission levels
- Option to use a vacuum system for altitude tests.

Available high-pressure propellant supply systems (the pressure quoted below is measured at the specimen interface) are as follows:

- Liquid oxygen (LOX): 360 bar, max 8 kg/s
- Liquid hydrogen (LH₂): 360 bar, max 3 kg/s
- Gaseous hydrogen (GH₂): 360 bar, max 1.5 kg/s; variable temperature down to 100 K
- Gaseous natural gas (GNG): 280 bar, max 3.5 kg/s
- Liquid natural gas (LNG): 250 bar, max 5 kg/s
- Cooling water supply: 200 bar, max. 50 kg/s
- Test times of up to 15 seconds at maximum mass flow
- High-precision mass flow regulation valves with an accuracy of max 1% mass flow level deviation and also fast operating point changes (<1sec).

Control Building P8

The control room for P8 is located in the D68 building which houses the central measurement and control systems for test facility operation, as well as various laboratories/workshops and office rooms.

Operating the bench is performed by means of a decentralized real-time computer system. The backend system is in D68 and all the frontends (measurement and control) are located at P8.

2.10.3 Users and Current/Future utilization

The facility is still operated under the Memorandum of Understanding already mentioned. This has been in place for more than 20 years.

The Department of Test Facilities is responsible for operating this bench. A scientific and a steering committee supervise the commissioning of the facility. Members of both the scientific and the steering committee are representatives from the different entities currently involved in the MoU for P8. These are:
- The French Space Agency CNES
- Airbus Safran Launchers
- DLR.

The steering committee is headed by the DLR Director of Lampoldshausen's Institute of Space Propulsion.

The need for renewals and upgrades is also addressed and decided upon by these two committees and the necessary financing is divided up according to the MoU.

The test results obtained at the P8 test facility are often used as calibration data for the verification of computer-based modelling tools.

Also the P8 is used as an economical subscale test facility to perform parameter studies on present or future European rocket engines or to validate problem fixing solutions in development engines.

Tests at the P8 are performed to verify new ignition methods (laser), new injection elements, new materials (ceramics) or new manufacturing procedures (ALM laser manufacturing).

In addition to rocket engine technology also systems for test bench operation (e.g. altitude systems / supersonic diffusor, noise suppression systems) are developed at P8.

For the future more emphasis will be put on the fact that not only thrust chambers, but also turbo pumps and complete rocket engines including turbo pumps will be evaluated at P8. A third test cell with the designation P8.3 is planned to be installed there by 2018, which will be able to accommodate such applications. The operating regime of this extension is within the same range as the current P8 facility. This asset will greatly increase the functionality of this unique test facility.

2.11 M11 Test Complex Overview

The first section of test complex M11 at Lampoldshausen with two test cells and a small office and laboratory building was built in 1966. Since these days the test facility is used to carry out tests and research on rocket and ram-/scramjet propulsion. The facility has since then been enlarged and refurbished several times. The physico-chemical laboratory was transferred to the M2 building in 1992, nevertheless propellants for the test runs are still prepared and produced at the G49 installation on-site at the M11 test ground.

The test facility is operated by the Propellants Department and work is currently focused on research into advanced green and gelled propellants and on hybrid and scramjet propulsion. Tests on projects funded internally by DLR and also by external partners are performed at the test complex, e.g. Rheform, ITEM-FK, ATEK, Future Fuels and ForTReSS. Further details about these and other projects can be found in chapter 4 and the activities and research results are described in chapter 1. The complex facilities offer also the possibility to be contracted out to external partners from industry, research organizations, universities and agencies.

Figure 2.39: View of test cells with test positions M11.1 – M11.4

2.11.1 The Test Positions

The installations at M11 consist of four test positions in two test cells, the M11.5 research and student test field and a propellant preparation and production facility in G49. Whilst each test position at M11 is equipped for carrying out a specific type of experimental activity a high degree of flexibility is still offered and the latest measurement and control systems are standard everywhere. 200 bar gas supply systems for H₂, O₂, and N₂ and pressurized air are available and all the valves and pressure regulators of the test benches are controlled by a redundant Siemens SPS. Additionally each test position features a system of versatile measuring devices which can be optimized to suit the specific test requirements, whereby combustion, flow and spray tests with a wide range of different rocket propellants can be conducted. Furthermore the simulation of relevant ram-/scramjet combustor entrance conditions or generally the testing of various propulsion hardware components and materials is possible.
**2.11.1.1 M11.1**

The M11.1 test position has an air heater (air vitiator with makeup oxygen) with hydrogen/oxygen burners (Figure 2.40). These burners produce “vitiated” air with the same oxygen content as the surrounding air due to the addition of makeup oxygen. With this setup ramjet and scramjet combustor air entrance conditions relevant for flight Mach numbers up to approx. 5 can be simulated from several seconds up to several tens of seconds depending on the selected flow conditions. The mass flow of the compressed and heated air can reach values of up to 5 kg/s with temperatures of 1500 K. Currently M11.1 is being used for research into combustors for scramjets. The focus is on studying boundary layer phenomena within a transpiration cooled section, where hydrogen is injected through a porous wall.

![Figure 2.40: Air vitiator with mounted entrance nozzle](image)

**2.11.1.2 M11.2**

A high altitude simulation test facility is currently under construction at the M11.2 test position for testing thrusters using green propellants. The facility has been designed for thrust levels up to 200 N and a maximum test duration of 15 s. A two-stage nitrogen ejector will reduce the pressure in the test chamber to 8 mbar for ignition testing, whilst under steady state thruster operation a pressure of under 30 mbar will be maintained. The thruster will be installed in a large tank (4 m³) with optical access, as shown in Fig 2.40. The facility has been designed with a high degree of flexibility so that various propellants, thruster designs and igniters can be tested.

Spray tests were being carried out at the M11.2 test position up to now. The atomization of non-Newtonian fluids and in particular gels with an impinging jet injector was investigated in detail focusing on their distinctive features in comparison to Newtonian fluids. The atomization of water and aqueous salt solution under near vacuum conditions was studied, focusing on flashing (a violent atomization caused by a partial evaporation of a liquid exposed to pressure below its vapor pressure) and cavitation. The primary diagnostic technique used was high-speed shadowgraphy.

![Figure 2.41: Vacuum chamber with model combustion chamber for green propellants](image)

**2.11.1.3 M11.3**

At test position M11.3 research is being carried out on the combustion processes of hybrid rocket fuels in a basic experimental setup. Solid fuel slabs are positioned in a rectangular combustor with windows to enable optical diagnostics. Currently paraffin fuel blocks, which are able to liquefy at their surface, are burned using gaseous oxygen. An H₂/O₂ torch igniter is used for ignition. At this model combustion chamber a high-speed camera enables high quality videos of the combustion, liquefaction and ignition processes. The focus of the research is on increasing the combustion efficiency and analyzing instabilities. Currently the experiments are being conducted under ambient pressure conditions, but a combustion chamber for pressures of up to 20 bar will also be implemented.
2.11.1.4 M11.4

The M11.4 test position is used for investigations on the combustor processes i.e. injection, evaporation and combustion of gelled propellants. The gelled propellants are stored in easily exchangeable piston-type accumulators, so-called cartridges. Using hydraulic drives with a continuously adjustable control, the gels are fed with exact and freely selectable mass flow rates through the feed pipes to the injectors. For a reliable and smooth ignition usually an H₂/O₂ gas torch igniter is used and the start of the combustion can be boosted by an auxiliary injection of oxygen. A 100 l/10 bar water tank is available for emergency cooling and purging. The test position is also equipped with a high pressure water cooling system providing up to 1.2 m³ H₂O at up to 200 bar although recent research has not made use of this particular infrastructure. A comprehensive selection of measuring instrumentation for e.g. thrust, pressures and temperatures as well as optical diagnostics is available. The DAQ system was renewed in 2016 and allows simultaneous acquisition of up to 160 channels. It also features unique capabilities e.g. an integrated test database and redline monitoring.

A set of modular, capacitively cooled combustion chambers with different diameters and lengths has been used for the determination of the characteristic length $L^*$. The $L^*$, which is the ratio of combustion chamber volume to nozzle throat area, is a specific performance characteristic for the gel propellant investigated and indicates the required combustor size. It is a valuable measure in order to realize compact but efficient rocket motors. Furthermore, two model combustion chambers with windows allow access for optical diagnostic tools enabling the visualization and investigation of the combustor processes.

2.11.1.5 Test Field M11.5

In 2013 the M11 test complex was extended to include M11.5, which is intended for research and student activities, e.g. within the STERN program (chapter 4). Two test containers can be placed on the test field. The containers offer a flexible platform for a wide range of tests. They can be prepared outside of the test field and then set up in place for a test campaign, thus a continuous exchange of containers reduces the set-up time on the field.

The test field is operated by remote control from a separate control room. Nitrogen and nitrous oxide gas are supplied via feeding lines to the containers. Power supply (360V, 220V and 24V) and data transfer are available via connection points at the rear wall.

One container on the test field is owned by the student group "HyEnD" from the University of Stuttgart which is funded by the STERN program. The students are conducting hot gas tests with hybrid rocket engines with a thrust level up to 10 kN.

The second test container is used by the Institute and serves for investigating the technological
development of future, green satellite propellants. The research focus is on the combustion and ignition behavior of such new propellants. During the last few years combustion tests with ADN-based propellants and tests with nitrous oxide/ethane mixtures were carried out here.

2.11.2 Physico-Chemical Laboratory

2.11.2.1 M3 Laboratory Wing

Due to various interface functions, the supporting facilities play an important role as regards providing specific lab services and in their function as a research establishment. The emphasis is on chemical analysis, development and prequalification of new advanced fuels. For this reason the M3 laboratory wing is equipped with a large number of various modern instrumental analytics.

This opens up completely new opportunities for the fundamental understanding of a propellant’s chemistry in the liquid or gaseous state, ranging from trace metal analytics up to comprehensive surface analysis.

General services and tasks are primarily:

- Offering a range of services for other departments
- Chemical analyses for external partners and customers
- Provision of laboratory infrastructure and personnel for research efforts
- Utilization as an educational establishment for students and trainees
- Performing advisory functions regarding chemical issues.

2.11.2.2 Small Scale Propellant Preparation Facility G49

The physico-chemical laboratory includes a small facility in which propellants can be prepared and produced. The handling of these materials is subject to the German Explosives Act. The production facility’s top priority task is to produce liquid and gel-like fuels for internal and external customers. Lab-scale quantities of propellant can be produced here. Two dissolver devices are available for the production of various gelled fuels and oxidizers. They are physically separated and are especially suitable for the production of gels because they can produce high shear rates.

Green liquid propellants based on energetic ionic liquids are produced and processed via micro-filteration. Using this method the finished products are tested for their quality and passed on to the researchers as a basis for further study.

The tasks of the propellant preparation facility can therefore be summarized as follows:

- Provision of adequate quantities of fuels (gel-like and liquid propellants)
- Processing and quality assurance of the prepared propellants.

For this reason the physico-chemical laboratory makes an important contribution to research programs and projects.
3. Department of Safety, Quality and Facility Management

General

Day to day operations at the Lampoldshausen site with its unique test and supply facilities are subject to German law. The relevant restrictions in this particular case come under the Bundes-ImmissionsSchutzGesetz and its related ordinances, (derived from the European SEVESO-II directive) and in particular the Hazardous Incident Ordinance. Because the basic conditions governing the effort to guarantee safety and security are so complex, Lampoldshausen has invested in personnel and introduced special processes in order to comply with the relevant legal restrictions as well as to guarantee personal health and safety and to protect the environment. The department of safety, quality and technical services employs a team of about 40 qualified members of staff who maintain the very high standard of performance necessary.

In addition to the essential tasks involving the protection of people and the environment, the department has a number of other important tasks on the site at Lampoldshausen, such as:

- Operating the Safety and Emergency Management System according to the statutory regulations on hazardous incidents (SEVESO-II-Directive)
- Abiding by and upgrading the operating permits
- Keeping up and improving the Integrated Management System – IMS
- Quality assurance for operation and maintenance of all test facilities
- Ensuring an uninterrupted supply at the Lampoldshausen site of water, energy, air conditioning/plenum system and pressurized air
- Operation of the waste water treatment plant
- Site maintenance and car service.

All these tasks and services are needed so that ESA’s test facilities for the ARIANE 5 and the other programs run smoothly. Special processes have been implemented to manage the requirements of third parties, e.g. Airbus SL.

The challenge is to keep within all existing and forthcoming requirements regarding existing and planned test programs and synchronize them with the relevant German and/or European laws. It is the department’s main duty to make sure that the exclusive operating license in Europe is valid and DLR can perform tests with cryogenic and storable propellant stages. An additional main task is also to supply the whole site with everything needed to fulfill all the partners’ requirements and provide them with support.

Organisation

The department is divided into three sections, i.e. safety and emergency, quality and facility management. The Department Head is also the hazardous incidents officer of the site and reports as such directly to the Director of the Institute. Furthermore he acts as an interface to the regional council and all other relevant authorities in terms of safety, health and environmental aspects concerning authorization on running the site.

The main tasks of the sections are described as follows.

3.1 Safety and Emergency Management

Safety and Emergency Management is divided into 3 areas and is dealt with by the safety operating team, the plant fire brigade, and a qualified paramedic. All activities concerning safety and emergency are coordinated from the control center. All test activities as well as emergency calls, fire or gas alarms, are collected and managed by the operator. In case of additional support the operator has direct contact to official authorities by phone or radio.

Figure 3.01: View inside the safety control center.
3.1.1 Overview of Tasks

- Operation authorization
- Operational safety and emergency management for test activities
- Fire prevention and protection
- Security services
- Operational safety provisions and concepts
- Occupational safety and health care
- First Aid
- Emergency calls (24/7)
- Environmental protection
- Providing training in safety, environment protection and health
- Emergency and evacuation exercises
- Maintenance of all safety and rescue devices such as fire protection, gas warning and control systems
- Maintenance of extinguishing agents, fixed firefighting systems and first-aid facilities
- Management of all malfunctions of the surveillance systems (24 hours a day)

3.1.2 Continuous Improvement

The Institute of Space Propulsion is aware of its responsibility for the safe handling of all test activities and makes every effort to continuously improve its safety and emergency management. Some of the measures are described in the following sections.

3.1.2.1 Emergency Management

Emergency and Evacuation Exercises

In 2011 the Institute of Space Propulsion introduced emergency and evacuation exercises to take place on an annual basis as opposed to the legal requirement of one exercise every three years. These exercises are conducted without advance notice and the location (office buildings or test benches) is chosen at random. They include all aspects of disaster relief as mentioned above. A thorough and realistic evaluation is carried out of the results of these exercises based on questionnaires and photo documentation. Lessons learned during these exercises are implemented directly to improve emergency plans.

Figure 3.02: The plant fire brigade.

Rearrangement of Assembly Points

The results of several emergency exercises were used to improve the overall layout and the infrastructure available at the site’s emergency assembly points. Several assembly points were relocated in 2011 and infrastructure was added which exceeded the legal requirements for emergency assembly points. For example, emergency telephones were installed and permanent first aid kits were made available.

Availability of Safety Information Specific to Each Building

In addition to standard escape and rescue plans on each floor of every office building, signs listing how to react in case of fire or in case of a gas alarm are being hung in every office in German and English. This measure exceeds the legal requirements.

Figure 3.03: An emergency and evacuation exercise at the M3 office and laboratory.
3.1.2.2 Safety Management

Electronic Access System

An electronic access system located at the site’s main entry gate was installed in 2015 to monitor staff members entering or leaving the site. While employees are required to use their badge to access the site, visitors and employees of external companies can only enter and leave the site after being checked by the security personnel. This means that the total number of persons present on the site at a given time is under continual surveillance, which is crucial in case of an emergency and/or evacuation.

Figure 3.04: Electronic access system

Safety Instruction Video

Safety regulations require all employees and visitors to the site to participate in safety drills on a regular basis (annually or every three years). Members of the safety department hold these training sessions in German (and in English on request) on a weekly basis. Visitors who have not taken part in a safety drill required to be accompanied by an employee of DLR or ASL on site at all times. A safety instruction video was made in 2016 to ensure greater flexibility in the handling of these procedures and to reduce time loss for DLR/ASL employees. This video will run non-stop in the entry building starting in 2017.

3.1.2.3 Healthcare

Installation of Heart Defibrillators

If anyone experiences a cardiac arrest or ventricular fibrillation on site the first minutes are crucial to their survival. Due to the isolation of the site it is imperative that special measures are in place just for this eventuality. To increase the chances of survival, 17 fully automatic heart defibrillators were installed at strategical locations throughout the site in 2014. By using one of these defibrillators the user can tell whether someone is suffering from a cardiac arrest or ventricular fibrillation. The device can guide untrained first aiders on proper usage. In addition, all employees can take part in training sessions in the use of defibrillators on an annual basis. Participation in these courses is mandatory for members of the fire brigade, the safety control center as well as for the primary and voluntary paramedics.

3.2 Quality Management

The quality section is mainly assigned to the different ESA projects on site in Lampoldshausen. The head of the team is also the management representative of the integrated management system.

The 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 customers’ test samples
- Configuration management of the test samples during test campaigns.

The quality engineers supervise all ESA project processes and check whether they comply with the relevant procedures. The procedures are part of the Integrated Management System (IMS) which guarantees a high quality, safety and environmental standard of all relevant test activities. For this reason yearly audits are performed to retain certificates to comply with DIN EN ISO 9001, DIN EN ISO 14001 and BS OHSAS 18001.

3.3 Facility Management

The technical services on site are part of the facility management group which is still in the process of being set up. One team is responsible for operation, maintenance and the upgrading of the electrical supply network and control systems to meet the general demands of the site, such as:

- 20 kV- and 6 kV- power grid
- 400 V supply system
- 230 V supply system
- Emergency power supply
- UPS (uninterruptible power supply)
- Command and signal network for the hazard alert system, IT, telephone, light signals and other services.

This team also supports the research and test facilities by finding solutions for special applications as regards to power supply.

Figure 3.05: View inside the E15 transformer station.

Another team operates and maintains the complex water supply system on the site, making sure that drinking, cooling, distinguishing and ultrapure water is available and it meets the necessary strict requirements. They are also responsible for the operation and maintenance of the waste water plant. This plant dates back to 2010 and meets all current regulations:

- A well on site for drinking and process water (7 l/s – 1 l/s)
- 2 water towers with a capacity of 600 m³ for process water
- A water tank for drinking water
- A distribution network for ultrapure water
- A biological water treatment plant
- A mobile air compressor.

Both teams support all kinds of tests and research activities on-site and assist customers and visitors in the best way possible.

The third team supports the institute with all other essential services such as:

- Site services
- A winter service to provide staff and visitors with a safe access to the site and to the depots and facilities especially provided in case of danger
- Waste management
- Purchase of new cars and disposal of the old ones
- Maintenance of all cars on site
- On-site transportation.

A number of new projects are in the pipeline to meet future requirements from a customer’s point of view, to satisfy the legal authorities and to meet the demands set by high safety and technical standards. Plans are being made to look into:

- Constructing a new heating system in addition to the existing one based on two block heat and power plants
- Refurbishing and extending the drinking water system
- Setting up a control center for the fire department, a safety center and first aid facilities
- Increasing the size of the parking area and building a new parking facility
- Reorganizing access to the main entrance for pedestrians and cars
- Installing a new siren system for early warning and announcements.

These measures will prepare the site for all kinds of future challenges.
4. Projects, Technology Transfer and Cooperation Activities

4.1 Projects

4.1.1 DLR-Projects

4.1.1.1 ProTau

Duration: 2014-2016
Partner: DLR Institute of Space Propulsion (project lead); DLR Institute of Aerodynamics and Flow Technology; DLR Institute for Combustion Technology

Project Description:
ProTAU combines the skills of three DLR institutes to increase DLR's capabilities in the numerical simulation of rocket engines. The DLR in-house flow solver TAU has been developed and enhanced to deal with rocket combustion as well as test bench problems. This covers specifically the implementation of real gas equation of state, fluid-structure interaction and the coupling with a Lagrange solver to simulate two-phase flows.

The TAU code is validated against experimental data obtained during measurement campaigns with dedicated test specimens at the DLR facilities in Lampoldshausen. The project is divided into four subtasks: Combustion Chambers, Nozzles, Test Facilities, and Heat Transfer in Cooling Channels.

The "Combustion Chamber" task consists of developing and validating the TAU code for the injection of oxygen at supercritical pressures. The real-gas model has been successfully implemented and validated against experimental data from the literature and from DLR BKC and BKH combustors. These chambers have an optical access so that data on the flame and LOX-spray extension is available for detailed comparison with results from the simulations. Specifically the TAU code is applied to analyze combustion instability problems in LOX/H₂ high pressure combustion chambers. Information regarding the impact of forced pressure oscillations on the flame dynamics is gained from numerical data and compared with results from experiments.

The “Nozzles” task includes studying and assessing flow behavior in stiffly deformed nozzles by conducting experiments and numerical analyses. The transition behavior of dual bell nozzles under cold flow conditions is studied in detail. There are plans to extend the study to simulate numerically the separation and transition behavior of ovalized dual bell nozzles. The fluid-structure interaction based on the TAU and NASTRAN codes has been implemented.

The objective of the “Test Facilities” task is to develop numerical methods and validate them for the simulation of high altitude test chambers under ambient and high altitude conditions. The point of this is mainly to gain a better understanding of the altitude chamber behavior and to improve nozzle test techniques in high altitude test facilities. TAU is applied with regard to sub-scale and full-scale test facilities. This task further develops capabilities to simulate full-scale experiments of combustion, two-phase flow and heat transfer under test bench conditions as in the case of, for example, Vinci.

The aim of the "Heat Transfer in Cooling Channels" task is to develop and validate the prediction ability of TAU regarding heat transfer in cooling channels. This specifically requires extended turbulence modelling and thermal fluid structure interaction. A dedicated experimental system will be set up at DLR Lampoldshausen and validation data will be generated for comparison with predictions.

Currently a new project called TAUROS is in preparation to deal with the further development of numerical expertise with a specific focus on multiphysics problems, complex computational domains, and new modeling approaches for the interaction of turbulence with combustion. Like ProTAU the TAUROS project will benefit from the joint co-operation of DLR's numerical and experimental experts.

4.1.1.2 LUMEN

Duration: 2014-2016 / 2017ff
Partner: DLR Institute of Space Propulsion (project lead); DLR Institute of Aerodynamics and Flow Technology; DLR Institute Structures and Design; DLR Institute of Space Systems

Project Description:
The aim of the LUMEN Project (Liquid Upper Stage Demonstrator Engine) is to improve DLR's know-how
related to rocket engine systems. It combines DLR’s existing capabilities on the basis of single engine components and processes. The objective is to improve the understanding of overall engine system behavior as well as the behavior of individual components within the engine environment.

To reach this goal in the frame of the LUMEN project a small-scale bread-board rocket engine demonstrator will be developed, assembled and operated on P8, the European research and development test bench. The propellant combination of LOX/LCH₄ will be used and the demonstrator will operate in an expander-bleed cycle layout. This combination offers reduced technological risks and is highly relevant for future reusable launcher applications. The thrust level of 30 kN was selected to be in the operation range of the test bench. Even so, there will be a strong similarity between the demonstrator engine and rocket engines designed for flight applications in terms of thermodynamic behavior. Due to its bread-board nature, it will not be optimized towards size and mass as real flight-like hardware. This means that the design will allow for wide-ranging measurement devices.

The main project tasks are sub-divided to deal with the engine’s subcomponents and relevant functions.

The major work package called “System” covers aspects of the engine system including stationary and transient cycle analysis, systems engineering, life prediction and health monitoring as well as features concerning the stage interface. The stationary cycle analysis in conjunction with the system-engineering part is responsible for providing design boundary conditions for the individual subcomponent designers.

The “Thrust chamber” work package includes tasks for the design of the sub-components injector head, ignition system, combustion chamber, nozzle extension and secondary engine systems (e.g. valves and pipes).

The “Turbomachinery” work packages focus on the design and development of simplified turbo-machines adapted for test bench application and operation with LOX and CH₄.

The “Numerical investigations” section covers several detailed investigations to be conducted according to the main key problems inherent to LRE development. This includes for example the coupled calculation of combustion zone and cooling channel heat pickup.

There will be experimental results to validate these findings.

The work package on “Testing” covers all aspects of test preparation, test sequence definition, test performance map construction and subsequent data reduction.

The LUMEN project will provide a platform for in-depth investigation of rocket engine system behavior. It will improve the existing tools for the design of complete engine cycles and their subcomponents as well as augmenting DLR’s know-how in the evaluation of existing and future rocket engines. The results and the experience gained will directly benefit the X-TRAS project team, whose objective is to advise the Board of DLR on future launcher design.

4.1.1.3 SeLEC
Duration: 2016 - 2018
Partner: DLR Institute of Space Propulsion
Project Description:
The SeLEC (Selective Laser Melting for Engine Components) project includes the
− design
− demonstration and optimization of Additive Layer Manufacturing (ALM)
− close-to-reality test of selected components of liquid rocket engines by the most widely used ALM technology: Selective Laser Melting (SLM). Three rocket engine components are currently in the design phase and are designated for manufacture and testing under SeLEC parameters:
  − a liquid rocket combustion chamber face plate with an innovative injector design (cone injector)
  − a liquid rocket engine turbo pump impeller
  − a segment of the inner liner of a liquid rocket engine chamber wall.

As part of the manufacturing process parameters are being developed and optimized for setting up the control of the Selective Laser Melting device and the suitability of alloy powders is being tested for the production of the above-mentioned LRE components. Production methods will be enhanced by:
− extensive tests with uni-axial test samples made from the SLM material
− finite element analyses of the LRE components manufactured using SLM.

In the final phase of the SeLEC project a series of near-to-real-application tests are planned:
− water flow (spray) tests with the above mentioned LRE faceplate
− spin tests with the above-mentioned LRE turbo pump impeller
− (high-performance laser-based) fatigue life tests with the above mentioned LRE chamber wall segment - a so called Thermo-Mechanical Fatigue (TMF) panel with nozzle throat geometry of a selected reference engine.

In the long term this research work is expected to pave the way for both:
− cost reduction - especially if conventional manufacturing technologies require complex assembly upgrading due to line-of-sight restriction of each of the single conventional production steps and/or one of the conventional production steps requires a very long production time (as in, for example, the galvanic deposition of metal layers)
− new design flexibility with the potential for reducing weight.

4.1.1.4 X-TRAS

Duration: 2013-2016
Partner: DLR Institute of Space Propulsion (project lead until 2015); DLR Institute of Aerodynamics and Flow Technology; DLR Institute Structures and Design; DLR Institute of Composite Structures and Adaptive Systems; DLR Institute of Space Operations and Astronaut Training; DLR Institute of System Dynamics and Control; DLR Institute of Space Systems; DLR Institute of Combustion Technology; DLR Institute of Materials Research;

Project Description:
The main objectives of the X-TRAS project are:
− making recommendations to the DLR Board at short notice (‘rapid action’)
− intensifying DLR space inter-institutional cooperation and thus increasing “one-DLR” knowledge
− creation of a European launcher strategy in close association with CNES and ASI
− assessment of launcher concepts on systems as well as on a sub-system level → advising DLR’s Board in a solid technical context
− identification of weak points in the knowledge base of the individual institutes to improve the quality of the given assessments
− “knowledge preservation” and “knowledge management” in the space transportation sector
− fostering a closer integration of the X-TRAS team into the European space community.

The X-TRAS project was launched in 2013 and prolonged in 2015. As the project focuses on actively advising DLR’s Board on space transportation issues, it will be very likely extended beyond 2016. Since the beginning of the project, advisory activities have been very extensive.

The X-TRAS project proved itself to be particularly helpful in preparing the ministerial conference in 2014. Several launcher system studies for different configurations (PPH vs. A6-like configurations) had been carried out before the conference and shown to the DLR Board.

The DLR Institute of Space Propulsion was responsible for managing the project until 2015. In addition to the project head, the Institute of Space Propulsion provided personnel to assist in launcher studies and to contribute rocket engine related information. The support in carrying out launcher studies and “rapid action” assessments for the most part took the form of engine system analyses. These cycle studies provided high level engine performance data for further use in the design of launcher stages.

4.1.1.5 AKIRA

Duration: 2016 – 2019
Partner: DLR Institute of Space Propulsion; DLR Institute of Space Systems (project management) DLR Institute of Flight System Technology; DLR Institute of System Dynamics and Control Technology

Project Description:
The following preparatory work for the DLR project called AKIRA (Ausgewählte Kritische Technologien und Integrierte Systemuntersuchungen für RLV Anwendungen) has been carried out in 2016:
− RLV literature study
− definition of RLV mission requirements
− preparation of the flight devices designated for capturing the in-air flight demonstration as included within the framework of AKIRA
− extension of the existing 3-DoF und 6-DoF flight path prediction models (for stiff systems) in order to take account of a simple flexible system
− improvement of an existing structural analysis model based on a device used to study deformation processes and damage parameters to include the effects of “thermal ageing” and “crack closure”. The model will include upgrades to cover all aspects occurring during the cyclic deformation of inner liners of combustion chambers of liquid rocket engines.
− (external contract:) Uni-axial tests with samples made from the AKIRA TMF panel material (including measuring optical deformation in order to account for deformation localization effects in the center area of the necked samples)
− the design of new (monolithic) TMF panels (with geometric parameters chosen according to the inner liner of the nozzle throat section of Vulcain I).

When completed this work will provide a solid basis for the work in connection with the Re-usable Launch Vehicle (RLV) planned from 2017 to 2019 within the time scale of AKIRA:
− sub-scale demonstration of the in-air capturing of a launcher booster stage
− demonstration of cryo insulation technology for launcher tanks with integrated health monitoring
− optimization of key geometric parameters of inner liners of LREs such as wall thickness, fin width as well as the width and the height of LRE chamber wall cooling channels to prolong service life and reduce fatigue.

4.1.1.6 SILA

Duration: 2016 – 2019
Partner: DLR RA Rocket Propulsion
         DLR RA Test Facilities
         DLR RA Testing Technologies

Project Description:
The SILA Project (SIde Loads and Acoustics in rocket engines at DLR Lampoldshausen test benches) is a combined activity of the Rocket Propulsion, Test Facilities, and Testing Technologies departments at the DLR Institute of Space Propulsion. The project addresses phenomena generated at the interface between the tested rocket engine and the test bench and its environment.

Noise Emission During Engine Tests

The objective of the acoustic investigation of the DLR test benches is to gain a better understanding of the noise emission mechanisms, the spatial distribution and the resonance frequencies. Indeed, the noise emitted during tests not only interacts with the environment but can also induce an acoustical feedback with the engine. A new measurement system will be developed and utilized at the various test facilities. Cold flow tests at P6.2 will be used for its qualification and optimization. A common method for every configuration will provide comparable data. The measurements will enable the identification of the natural and resonant frequencies. The new microphone array will provide a spatial distribution of the noise generation depending on the test configuration. This information will theoretically result in discovering better noise damping routines and allow optimization of facility configurations regarding noise limitation. A data base will be generated regrouping existing and newly generated measurements. It will be made available to the three participating departments.

Side Load Reduction Device (SLRD)
The main objective is to study the SLRD regarding its suitability for use at test benches and possibly on the start ramp for rocket launches. The proposed work will have two aspects, firstly the optimization of the SLRD concept and then the verification and application to hot flow, full-scale conditions. It is relatively easy to verify the high potential of the SLRD concept on various test bench facilities and for various engine configurations as it requires only small bench modifications. The challenge will be to evaluate the additional risks possible and adapt the risk analysis and test sequences for each facility. This task will require good teamwork between the departments involved. At the end of the three year funding period the investigation of the SLRD concept should have reached a level of understanding necessary for conducting the preliminary design review (PDR) for
the application with view to initiating full scale test facilities at P5 and/or P4.

4.1.1.7 Future Fuels

Duration: 2015 - 2017
Partner: DLR Institute of Combustion Technology (project lead); DLR Institute of Space Propulsion; DLR Institute of Engineering Thermodynamics; DLR Institute of Solar Research; DLR Institute of Propulsion Technology; DLR Institute of Atmospheric Physics, DLR Institute of Transport Research; and DLR Institute of Vehicle Concepts

Project Description:

Research into different kinds of new propellants and fuels is being carried out as part of the “Future Fuels” strategic project. DLR’s four research and development programs Space, Aeronautics, Energy and Transport are working closely together to combine their know-how as regards fuels and propellants. The emphasis of research as part of this project is on the improvement of liquid fuels and on alternative production paths for liquid hydrocarbons. Nowadays hydrocarbons are an indispensable energy source for transportation in air, space, on the road and at sea. Due to the increase in global challenges such as climate change and the finite availability of fossil fuels the search for alternative, regenerative sources for hydrocarbons is crucial.

The project’s goal is to investigate new propellants and fuels, analyze and evaluate the methods of synthesis and finally to test those fuels, propellants or additives. For example, the focus in the transportation and energy sector is on reducing carbon dioxide emissions, developing additives for current fuels and investigating the production costs of different fuel sources. Solar fuels, synthesis of fuels and newly designed propellants for the different areas of application are being studied in detail. The Institute of Space Propulsion’s “Future Fuels – Green Propellants” subproject focuses on the nitrous oxide and hydrocarbon premixed propellants and their ability to fulfill the needs of space and satellite applications. During the last two years teamwork on the project has led to countless positive and productive discussions amongst the participating institutes and created research-based synergies.

A detailed description of the fields of activity within the project dealing with nitrous oxide and ethane (HyNOx) mixtures can be found in (chapter 1).

The results of research into the ignition process and numerical simulations of combustion are examples of the success of the teamwork mentioned above. With help from the Institute of Combustion Technology reduced reaction mechanisms were developed and are currently being implemented in DLR’s TAU code for initial combustion simulations at Lampoldshausen.

4.1.1.8 ITEM-FK

Duration: 2015 - 2018
Partner: DLR Institute of Aerodynamics and Flow Technology (project lead); DLR Institute of Structures and Design; DLR Microwave and Radar Institute; DLR Institute of Space Propulsion; DLR Institute of Materials Research; DLR Engineering Facility (SHT)

Project Description:

The DLR project on “Innovative Technologies and Methods for Missiles” (ITEM-FK) combines activities on detection and analysis of threats imposed by missiles as well as the technology of their interception. The project represents an important part of DLR’s Defence and Security Research.

In conclusion, the project has three main strategic goals, which are:

- Development of innovative technologies and methods in the four areas of aerodynamics and missile control, application and manufacturing of innovative materials for missiles. The activities include working on innovative propulsion concepts including sensors and target acquisition
suitable for improving the performance of future missiles as regards range, speed, agility and accuracy.

- Extension of DLR’s expertise in the analysis and evaluation of missile technologies and systems, and

- Consequently, expansion of DLR’s “know-how” in order to support government and national industries in the development of future missile systems.

Several sub-tasks stem from these three strategic goals. They originate as a result of technology and methods developed in the specific work packages as well as from the fulfillment of their specific aims:

- Expansion of the simulation capabilities regarding missiles and their missions, as well as broadening of reference missile samples.

- More efficient control performance of missiles at low dynamic pressures.

- Improved performance of air-breathing propulsion for long range missiles.

- Development of a comprehensive knowledge base of the processes concerning gel propulsion systems in order to optimize process management and to support the enhancement of tools for the design and evaluation of gel rocket motors.

- Development of materials and manufacturing procedures for missiles components exposed to high structural and thermal loads.

- Improvement of the thermal management and analysis of missiles and components under high thermal load (esp. hypersonic missiles).

- Improvement of target acquisition and discrimination.

- Buildup or rather extension of an adequate expertise for the analysis of potential threats related to ballistic missile defense.

The Institute of Space Propulsion coordinates the main work package “upper tier interception” and is herein responsible for the work package WP 3500 on combustion chamber process characterization of gel propulsion systems. The objectives of this work package include the detailed analysis of the important combustion chamber processes i.e. injection, atomization, evaporation and combustion as well as the derivation of adequate models and correlations for their presentation (related to sub-goal 4). Such models are a prerequisite for the tools necessary in the design and development of gel rocket motors. Chapter 1 includes a detailed description of the work conducted at Lampoldshausen and the results achieved. Investigations carried out are currently the successful continuation of basic research and technology development work already completed as part of the predecessor projects HaFK, FFT, FFT-2 and FluTech. A large part of this work is also embedded in the German Gel Propulsion Technology Program (GGPT).

Figure 4.01: Hot fire test at test facility M11.4

4.1.1.9 ATEK

Duration: 2015 - 2018
Partner: DLR Institute of Aerodynamics and Flow Technology (project lead); DLR Institute Structures and Design; DLR Institute of Composite Structures and Adaptive Systems; DLR Institute of Space Propulsion; DLR Institute of Space Operations and Astronaut Training; DLR Institute of System Dynamics and Control; DLR Institute of Space Systems; DLR Institute of Simulation and Software Technology

Project Description:

The main objectives of the ATEK project (Antriebstechnologien und Komponenten für Trägersysteme) are the design, simulation, construction and instrumentation under the particular aspect of their reusability.

- Specifying the requirements for flight experiments with new components to increase reusability

- Design, construction and test of a CMC nozzle

- Design, construction and test of a down-scaled hybrid construction element
Design, construction and test of flight electronics and sensors with high data acquisition rates.

The DLR Institute of Space Propulsion is involved in work package 4600 to investigate combustion processes in a model hybrid rocket combustion chamber. This package focuses on fundamental research to evaluate in detail the combustion process of mainly liquefying hybrid rocket fuels.

These evaluations include the analysis of the combustion process as regards fuel composition, fuel slab geometry and combustion chamber set-up. Experiments are carried out with a basic hybrid rocket combustion chamber constellation with windows for optical access under ambient pressure. A new set-up is presently under construction to evaluate the combustion processes at higher pressure rates and compare them with previous results.

4.1.1.10 ForTrAS / ForTReSS

Duration: 2012 - 2021
Partner: DLR Institute of Space Propulsion

Project Description:

“ForTrReSS (Fortschrittliche Treibstoffe für den Satelliten- und Stufenbereich) (formerly ForTrAS) is a subproject of "Reusable Space Systems" and deals with the identification of suitable advanced green propellant fuels which could be of interest to replace hydrazines (N₂H₄, MMH) in attitude control systems of satellites and launcher stages. The results of this pre-screening work package contribute to the ongoing Rheform, Future Fuels and Propulsion2020 projects. It deals with several aspects which they cannot cover and is helpful in the preparation of future project proposals due to its contribution to an increase in basic research, development and know-how in connection with several new propellants.

After suitable propellant candidates have initially been identified the objective of phase I (2012 –2018) is the development of combustor process control of the selected propellants. The work with monopropellants is mainly focused on ADN based and nitrous oxide based mixtures. Furthermore, as a first step, interest will concentrate on advanced green bipropellants. Distinct ionic liquids as possible fuel sources with highly concentrated H₂O₂ (> 87 %) will be tested as single species oxidizer but also experiments with oxidizer mixtures, e.g. with ADN, are planned. The Institute of Space Propulsion will carry out preliminary work on the use of H₂O₂ (risk analysis, storage and feeding systems, handling, etc.) under the H₂O₂@TRS project. In Phase II of ForTrAS / ForTReSS (2019 – 2021) tests on further interesting fluids currently still under development will be carried out, like ionic liquids.

4.1.1.11 GGeRA

Duration: Preparatory phase in 2017. After final decision for funding in 2017: 2017-2020
Partner: DLR Institute of Space Propulsion (project lead); DLR Institute of Structures and Design; DLR Institute of Engineering Thermodynamics

Project Description:

The project on “Green Gel Propellants for Space Applications” (Grüne Geltriebstoffe für Raumfahrtrrelevante Anwendungen) was initiated in 2016 and has been approved by the space program directorate to run preliminarily for one year to start with this task. The focus of this program is on the identification of suitable versatile environmentally friendly and hypergolic gelled bipropellant combinations and the development of reliable combustion chamber processes including injection, mixing, vaporization and combustion as well as materials and technologies to handle the associated high thermal loads.

Green hypergolic gel propulsion systems could further increase performance (in comparison with gelled monopropellants) and simplify the ignition process so that a range of new applications is a possibility. Therefore different oxidizer gels based on e.g. hydrogen peroxide (H₂O₂) and ammonium dinitramide (ADN) plus different gelling agents will be evaluated on a laboratory scale. Fuel blends may consist of hydrocarbons or energetic ionic liquids as well as additives for ignitability. The newly developed propellant gels will be characterized both in spray and hot fire tests. Tests will also take place with combustion chamber components made from fiber-reinforced ceramics and with thermal barrier coatings.

The GGeRA project rounds off activities performed as part of the ITEM-FK and RFR projects. However, findings of this project are also very valuable for other projects on e.g. H₂O₂, hypergolic ignition and combustion chamber design as investigated in ForTReSS.
4.1.1.12 RFR


Partner: DLR Space Operations and Astronaut Training (in charge of the project: Mobile Rocket Base); Bayern-Chemie; DLR Institute of Space Propulsion; DLR Institute of Structures and Design; DLR Institute of Aerodynamics and Flow Technology

Project Description:

The "Research/Sounding Rocket Stage" (Raketestufe für Forschungsraketen) project deals with the design, manufacturing, testing and qualification of a versatile rocket stage of the MORABA standard performance class for different research requirements. During the current preparatory phase of one year a trade-off between a solid rocket motor and a gel rocket motor will be made. Engineering support and preparation for the qualification tests of the whole rocket stage (built by Bayern-Chemie) are in planning for the subsequent design and qualification phase at the Institute of Space Propulsion. The activities described here will benefit from experience gained from the ITEM-FK, GGPT and GGeRA projects as well as the institute’s comprehensive knowledge on testing techniques.

4.1.2 DFG Projects

4.1.2.1 SFB TRR 40

Duration: 2008-2020 (3rd phase 2016-2020)

Partner: DLR Institute of Space Propulsion, DLR-WK, DLR-IAS, DLR-BT, RWTH, TUBS, TUM, UBWM, US, Airbus DS

Project Description:

The SFB Transregio 40 addresses "Fundamental Technologies for the Development of Future Space-Transport-System Components under High Thermal and Mechanical Loads." The contribution of the DLR Institute of Space Propulsion covers two tasks:

- C7 combustion instability
- K2 dual bell nozzle flow under realistic flight conditions.
concentrated on understanding basic flow behavior by researching cold flow. During the second period the prediction standards were validated with hot flow tests. The results of numerical simulations also provide good prediction ability as regards nozzle flow behavior. The aim of the third period is to produce a study of dual bell nozzles for practical purposes. The effects of in-flight conditions are simulated in an altitude chamber. In association with the other TPs, the utilization of a dual bell as main stage engine nozzle is studied and the flight trajectory will be calculated to determine the maximum potential payload increase possible for a future Ariane configuration.

4.1.2.2 SFB TRR 75
Duration: 2010-2017ff
Partner: DLR Institute of Space Propulsion; University Stuttgart; University Darmstadt

Project Description:
The SFB Transregio 75 Collaborative Research Center is looking into Droplet Dynamics under Extreme Boundary Conditions. It comprises of three research areas:
- research area A: Methods and Fundamentals
- research area B: Free Droplets
- research area C: Droplets with Wall-Interactions.

Subtask B4 "experimental investigation of transient injection phenomena in rocket combustion chambers under high altitude conditions with special focus on flash evaporation" is DLR's contribution to research area B. The activity is presented in detail in section Research and Technology: Propellant Injection. The parameters of TRR75 define a close association with subtask B5 "Modeling and simulation of flash evaporation of cryogenic fluids", which is supervised by Prof. Kronenburg at Stuttgart University.

Data is being exchanged and the different teams are working together on increasing the understanding of flash vaporization processes of ionic liquids. ADN-based EILs are being simulated by using urea solutions.

4.1.3 EU Projects
4.1.3.1 ISP1
Duration: 2009 - 2012
Partner: DLR Institute of Space Propulsion as well as 15 European industrial partners, universities and research institutions from France, Germany, Italy, Belgium, Poland, Czech Republic and Spain

Project Description:
The European FP7 Collaborative Project, Focused Research Project Theme 7 set the parameters for the In-Space Propulsion (ISP-1) project which aimed at improving the knowledge and the techniques necessary for future space missions relying on cryogenic propulsion.

The ISP-1 program was split into five main work packages which dealt with various technological issues associated with the development of a low thrust cryogenic propulsion system. It concentrated on liquid oxygen, liquid hydrogen, and liquid methane propellants. The areas addressed by the work packages were LOX-methane combustion, hydrogen embrittlement, material compatibility and tribology in liquid oxygen, energy management of a low thrust propulsion system, and the development of electrically powered cryogenic turbo pumps. The scientific and technological goals assigned to each work package can be summarized as follows:
- combustion studies and testing focusing on low thrust LOX/CH₄ space propulsion with an emphasis on low pressure liquid injection
- compatibility and tribology analyses and tests addressing both technological features and more fundamental aspects of tribology
- hydrogen embrittlement studies (including hydrogen embrittlement modelling) and tests aimed at investigating how new materials react under high pressure and medium range temperatures and validating the above mentioned hydrogen embrittlement models
- heat accumulator studies and tests (under supervision at DLR's Lampoldshausen site), focusing on energy management techniques and on testing a low temperature accumulator at the Lampoldshausen M51 facility
- design an electric propellant pump and put it to the test, resulting in a demonstrator model for trials using LN₂.
The results of ISP₁ are as follows:

1. In terms of LOX/methane combustion, the second period of the project focused on acquiring and consolidating data from experiments and on building models for validation using the computational fluid dynamics (CFD) process during the second and remaining period.

Worley's soot model was used as a basis for a new version, but effects during operation showed how important it was to develop a dedicated model for combustion in pure oxygen. Low pressure kinetics was also derived involving 24 species and 103 reactions.

On the subject of experiments a Coherent AntiStokes Raman spectroscopy (CARS) campaign was conducted, as well as ignition campaigns carried out at both ambient and low pressure. The requirements were very well defined which is very important for subsequent CFD analyses.

On the subject of CFD analyses, RANS (Reynolds-averaged Navier-Stokes) computations were made at the nominal working point of the ISP₁ engine for comparison with the CARS database. The flame length and final combustion temperature were ascertained with reasonable consensus but some discrepancies arose between results and CARS measurements in the flame. Nevertheless, these CFD analyses indicate several ways to enhance the methodology for CH₄ oxy-combustion modelling and computations.

Preliminary CFD computations were also carried out for ambient pressure ignition with a Large Eddy Simulation (LES) model.

2. For the purpose of hydrogen embrittlement research in total three materials were in the HCF regime: Inconel 718 and A 286 which were of immediate interest for industrial partners and Inconel X750 which was relevant for more fundamental studies on material law as successfully programmed and demonstrated for 2d Finite Element analysis at DLR Lampoldshausen.

3. The following activities took place regarding compatibility and tribology of LOX and methane in a cryogenic environment.

Experimental work was performed by pursuing two approaches: scientific research on the tribological behavior of materials in LOX, whereby tests in different environments were performed in order to better understand the contribution of the different potential mechanisms on the observed behavior. A more applied approach was used in order to assess the different materials to be used for the electric propellant pump in terms of compatibility and wear and tear. The study of a tribometer for tests in liquid methane was completed.

4. For the purpose of studying and modelling heat accumulators:

Improvements were carried out on a model for numerically analyzing the behavior of two phase flow phenomena in heat accumulators. The final version was based on a two-fluid model inside tubes and three-dimensional (3D) laminar and turbulent resolution (with LES models) of the heat transfer by convection in the phase-change material with structured meshes. The experimental setup especially developed for the validation of the numerical models was designed, built and tested at DLR Lampoldshausen with very comprehensive and highly accurate instrumentation.

4.1.3.2 ORPHEE

Duration: 2009 bis 2011
Partner: DLR Institute of Space Propulsion; SNPE Matériaux Energetiques, France; ASTRUM SAS; ASTRUM GMBH, Germany; AVIO S.P.A., Italy; University of Naples (DIAS), Italy; ONERA, France; Politecnico di Milano, Italy; Polytechnica University of Bucharest (UPB), Romania; THYIA Technologije, Slovenia

Project Description:

The Operational Research Project on Hybrid Engine in Europe (ORPHEE) tackles the subject of combining...
solid and liquid propulsion. This technology envisages within a single propulsion system a combination of:

- high performance
- wide-ranging throttle capability
- stop-restart options.

In the initial phase of ORPHEE the characteristics of solid fuels which are of potential interest were improved (e.g. by adding metallic powders in order to increase the fuel regression rate) and categorized in terms of small scale combustion. On the basis of an accurate study of the test results it was possible to get a description of the regression rate evolution according to the global mass flow rate and the geometric shape of the grain, and generate experimental data for the validation of numerical tools. However, it was noticeable that the impact of adding metal powders is much smaller in the larger scale experiments performed in the second part of ORPHEE.

Based on the above mentioned results the ORPHEE partners developed two hybrid engine road-maps. These road-maps focus on identifying suitable hybrid propulsion demonstrators solely for use in connection with space applications (selected through a market survey and system analysis). Finally technological demands were identified in terms of development and the associated time span required to reach a TRL value of 6 for the two demonstrators (including a feasibility study for demonstrator scale tests at P8 at the Institute of Space Propulsion in Lampoldshausen).

4.1.3.3 ATLLAS II

Duration: 2011-2015
Partner: DLR Institute of Space Propulsion
ESA / ESTEC (project lead); EADS-IW; MBDA; ONERA; FOI; ALTA; GDL; STARCS; TISICS; SOTON; USTUTT; UPMC

Project Description:

The Aero-Thermodynamic Loads on Lightweight Advanced Structures II (ATLLAS II) project focused on developing advanced light-weight material capable of withstanding high temperatures and strongly linked to a high-speed vehicle design with air-breathing engines.

The prime impetus setting the requirements for material manufacturing, processing and testing was a Mach 5-6 vehicle. The following work was performed within the specifications of ATLLAS II:

A. Detailed design of a Mach 5-6 vehicle with air-breathing engines:

The optimum Mach number theoretically calculated was 6, which would however require a combustor temperature of more than 2000 K.

A Mach number of 5 was therefore selected for the follow-on vehicle studies and was implemented for the 3 concepts taken into consideration.

- wave-rider
- lifting body
- conventional configurations (with a distinct wing and fuselage).

B. Aero-Frame & Materials Integration:

Hypersonic flight conditions expose aircrafts to temperatures that are beyond the limits of classical aircraft materials. For that reason the latest developments in new materials and composite structures suitable for high temperature application were taken into account in the context of ATLLAS II.

A large number of structural (tensile, fatigue and creep) tests were performed with uni-axial and bending samples made from the following materials:

- Ceramic Matrix Composites (CMCs) such as SiC/SiC and Whipox (with test temperatures up to 1200°C)
- Titanium Matrix Composite (TMC, with test temperatures up to 1000°C).

From Ultra High Temperature Ceramics (UHTCs) such as HfB₂ and ZrB₂ (both manufactured as compounds with 20% vol. SiC), oxidation tests were performed up to temperatures of 2000°C

C. Combustor and Material Integration:

A series of tests resembling real-life conditions under application were performed with high temperature materials:

- High Velocity Oxygen Fuel (HVOF) long duration material test on (small diameter) round and flat material samples made from Ceramic Matrix Composites (CMCs) such as C/C, C/SiC and C/C-SiC at temperatures up to 1600°C
- permeability tests of conical C/C and OXIPOL samples at elevated temperatures
D. Aero-Thermal-Structural Loads at High-Speed:
A series of numerical and experimental studies were carried out to define the thermal and structural loads of a hypersonic vehicle:

- calibration of models representing engineering laminar-to-turbulent boundary layer transition (including intermittency based ones) by means of detailed LES, experiments and RANS CFD
- experimental investigation into the impact of dynamic loads on thin metallic structures
- Large Eddy Simulations of shock impingement on a turbulent boundary layer.

Although the primary focus of ATLLAS II concentrated solely on flight with air-breathing engines both:
- the developed and tested (ultra) high temperature ATLLAS II materials and
- the improved (and to a certain extent also validated) numerical simulation models and tools of ATLLAS II
can also be applied directly to certain components of rocket based launch systems such as e.g. fly-back boosters and / or the SABRE combined cycle (air/breathing / rocket mode) engine, intended for the re-usable SKYLON space launch system.

4.1.3.4 GRASP
Duration: 2009-2012
Partner: Austrian Research Centers, passed to University of Applied Sciences Wiener Neustadt (project lead); DLR Institute of Space Propulsion; Swedish Defence Research Agency (FOI); SNECMA, France; CNRS, France; DELTACAT, GB; University of Southampton, GB; University of Naples, Italy; Evonik, Germany; Céramiques Techniques et Industrielles (CTI), France; Instytut Lotnictwa (IoA), Poland; Fotec, Austria

Project Description:
The GRASP (GReen Advanced Space Propulsion) project provided alternative ideas on propellant to European industry to find replacements for the highly toxic and carcinogenic propellants in current use (e.g. hydrazine, MMH, NTO).

These alternative, so-called green propellants reduce the potential risk to human operators and the environment and thereby also significantly reduce the associated handling cost. In the first phase of the GRASP project a data base of more than 100 Green Propellants was compiled.

This data base lists physical properties as well as information on the individual toxicity levels and performance. Using the information stored in this data base, a preliminary selection was made to identify the most promising choice of possible green propellant. As none of the green propellant combinations taken into account is hypergolic, several green propellant catalysts were manufactured, assessed and down-selected throughout the duration of GRASP.

Numerical tool development supported GRASP experimental activities:
- analyses of the heat transfer in monolithic catalysts and packed sphere heating beds
- 1d reaction kinetic models of H2O2 thrusters
- generation of the extended specific impulse measurement which can be used as a general (basic research work) criterion for ranking the performance of (green) propellants.

In the final phase of GRASP experiments were carried out on the chosen propellants which involved designing, manufacturing and testing model thrusters with different thrust levels:
- 1 N Bipropellant: HTP / Kerosene
- 20 N Monopropellant: HTP
- 20 N Monopropellant: FLP-106 (ADN based). (The tests were conducted at the M11 test complex in Lampoldshausen.)
- 200 N Bipropellant: HTP / Kerosene / Turpentine / Dipentene
- 200 N Hybrid: HTP / HDPE.

4.1.3.5 LAPCAT I and II
Duration: I: 2002-2008; II: 2008-2013
Partner: European Space Research and
Project Description:

Antipodal flights (that is, flights between two diametrically opposite points on the globe) take between two to four hours. The objective of LAPCAT I was to reduce this time frame.

LAPCAT II followed on by considering only two innovative concepts – for Mach five and Mach eight cruise flight - of the various vehicle studied in LAPCAT I.

Starting with the Mach five vehicle and the associated pre-cooled turbo ramjet developed in LAPCAT I, a more in-depth evaluation of the assumed numerical performance data was carried out of various components, i.e.:

- intake design and performance
- the environmentally friendly design of the combustor
- nozzle design and performance
- structural analysis.

Although the cruise flight of the Mach eight vehicle – based on a scramjet – seemed technically feasible, the fuel consumption during acceleration required a large fraction of the fuel with a negative impact on the gross take-off weight. Initial studies of a first stage rocket ejector concept resulted in the range being poor and take-off mass being large. Interest was centered on the integrated design of the airframe and engine throughout the whole trajectory to guarantee an optimal design in terms of range and flight time. Varying design drafts will be re-assessed and optimized to achieve a final Mach eight concept. Both turbo- and rocket-based engines will be examined more closely to ensure better performance and fuel consumption during acceleration and cruise phases. Important points that will be addressed to achieve these goals are:

- proper development and validation of engine-airframe integration tools and methodology
- high-speed air-breathing cycle analysis
- off- and on-design behavior of engine and airframe
- experiments with the explicit purpose of evaluating structures at various operating design points and dealing with aerothermodynamics, intakes, combustion and nozzles.

4.1.3.6 Rheform

Duration: 20015-2017

Partner: DLR Institute of Space Propulsion (project lead); Swedish Defence Research Agency (FOI), Sweden; Centre national de la recherche scientifique (CNRS), France; Forschungs- und Technologietransfer GmbH (FOTEC), Austria; ECAPS, Sweden; Airbus DS, Germany; LITHOZ, Austria

Project Description:

The Rheform project is funded under the European Union’s Horizon 2020 program. The acronym Rheform stands for: “Replacement of hydrazine for orbital and launcher propulsion systems”. Its goal is to replace hydrazine with ADN-based liquid propellants for orbital and launcher propulsion systems.

The two baseline propellants for the project are LMP-103S and FLP-106. As mentioned in chapter 1 these propellants require a combustion chamber made of materials that are currently restricted under ITAR. The project aims to develop and test new propellants compositions to lower the combustion temperature so that substances complying with ITAR regulations can be used as catalysts and in combustion chamber design.
Another focus of the project is to improve cold start capabilities and thus reduce the need for pre-heating the system. In order to achieve these goals two different courses of action will be followed. On the one hand work on improving the catalytic ignition system will be carried out and on the other hand there will be an assessment of thermal ignition systems. If necessary the possibility of combining catalytic and thermal ignition will be looked into and conventional systems such as torch igniters, as well as advanced systems such as laser ignition systems will come under examination.

The blend of propellant and the ignition routine will be verified using one or two demonstrator(s), equivalent to a TRL of 5. The project will look into adapting existing numerical models to describe the processes in the propulsion system. Possibilities for the optimization of the production process of ADN will also be studied in order to reduce the cost of producing this fuel.

4.1.4 ESA TRP Projects

4.1.4.1 Battleship Chamber for Unsteady Combustion Process Analysis

Duration: 2011-2012
Partner: DLR Institute of Space Propulsion
EADS Astrium

Project Description:

The aim of this project was to better understand the influence of hydrogen injection temperature on combustion stability in cryogenic rocket engines. Tests dedicated to the experimental investigation of unsteady combustion chamber processes were performed with a subscale combustion chamber (provided by Astrium) equipped with a dedicated measurement ring (designed by DLR) at the test facility P8 at DLR Lampoldshausen. A key feature of this campaign was controlled hydrogen temperature ramping (HTR) during the course of each test run. The goal of HTR testing is to determine the temperature threshold of hydrogen where combustor operation changes from stable to unstable. The hydrogen injection temperature was continuously reduced in the hopes of observing an instability onset event of the variety reported extensively in literature from the 1960s-1970s.

The experimental data obtained contributed towards improving existing knowledge on LOX/H₂ combustion instability. Globally, HTR results concur with findings published by NASA in the 1960s on the subject of instabilities in LOX/H₂ combustors. However, test data from another injector provided in-kind by DLR, exhibits behavior which contradicts the stability boundaries established as a result of the NASA findings. This is seen as a strong indication that other mechanisms encourage the stability behavior of this setup, and a follow-up project was proposed to investigate this presumption.

4.1.4.2 Cryogenic RCS Thruster Technology – Laser Ignition

Duration: 2010-2013
Partner: DLR Institute of Space Propulsion
ESA
Astrium Space Transportation
Carinthian Tech Research (CTR), Austria

Project description:

The purpose of this TRP was to identify potential applications of laser-induced ignition for RCS (Reaction and Control System) and OMS (Orbital and
Maneuvering System) engines, generate requirements based on these potential applications, design a breadboard thruster to examine the feasibility of laser ignition under representative conditions and subsequently build and test this thruster at a test bench.

The main testing activities aimed at identifying the feasibility of laser-induced ignition for use in space.

In particular, a new generation of RCS (Reaction and Control System) and OMS (Orbital and Maneuvering System) engines based on non-hypergolic propellants is being studied during the design phase. In addition to new and advanced propellants, classical propellant combinations are potential contenders such as O₂/H₂ and O₂/CH₄. The advantageous characteristics of these propellant combinations are their performance (Isp) and non-toxicity. On the other hand propellant combinations such as these need a reliable and lightweight ignition system.

The test campaign was extensive and covered 295 test runs. Overall the laser ignition tests have shown that this type of ignition has significant potential. Four main subject areas of plasma ignition were tested (near-faceplate, recirculation zone, shear layer, and downstream region) and laser pulse energies varying in range from 25 to 161 MJ.

Local flow field characteristics resulted in one main area where energy deposition was favorable, namely the shear layer downstream of the fuel Mach disk. A 100% ignition success rate was ensured where energy was reduced to 72 MJ and 92 MJ for LOX/GH₂ and LOX/GCH₄ respectively. Other ranges resulted in either extinguishing initial flame kernels or were associated with a reduction in the ignition success probability due to the stochastic nature of the oxygen spray.

The laser ablation tests were extremely successful in that the energy rate required of a laser beam focused on a copper target placed in the vicinity of the injector exit were as low as 61.7 MJ for LOX/GCH₄ and 14.5 MJ for LOX/GH₂.

Finally OH imaging and dynamic pressure measurements provided proof that ignition overpressure, which is frequently encountered in laser ignition, is determined by the direction of the flame development.

Upstream to downstream flame growth results in higher ignition peak pressures than downstream to upstream growth. Downstream to upstream growth could be observed when energy was deposited in the shear layer downstream of the fuel Mach disk. Where both energy aspects and ignition overpressure characteristics are concerned, the shear layer is the optimal location for energy deposition in plasma ignition.

Finally, laser ignition was identified as being of potential interest in a technical sense not only for non-hypergolic RCS/OMS. Three fields of application in which laser ignition is/could be relevant are:

- non-hypergolic RCS/OMS
- high thrust, i.e. as in main and upper stage engines
- test bench ignition systems.

A large number of tests concerning laser ignition for re-startable upper stage cryogenic engines and RCS/OMS applications were carried out by DLR and Airbus Safran Launchers as a result of this TRP.

4.1.4.3 Laser Ignition Technology for Rocket Engines

Duration: 2014-2016
Partner: DLR Institute of Space Propulsion; ESA; Carinthian Tech Research (CTR), Austria

Project Description:
The objective of this assignment was to design, build and test a laser ignition system for the cryogenic liquid propulsion of a launcher with the ultimate goal of gathering know-how for future use in the development of an operational upper stage cryogenic engine laser ignition system.

The following activities were completed:

1. Design of a light-weight, robust laser ignition system able to ignite cryogenic propellants in high altitude conditions.
2. Manufacturing and integration of the ignition system in a breadboard thruster able to reproduce the ignition phase of an upper-stage cryogenic expander engine.
3. A wide range of 122 ignition test runs with GH₂/LOX propellants in order to characterize different ignition parameters (e.g. target material, pressure, laser power).
4. Compilation of a test report detailing the findings.
5. Generation of a set of optimized ignition parameters that serve as a solid starting point for designing a laser ignition system for a full scale upper-stage cryogenic expander engine demonstration and further development.

Throughout the whole test campaign the specially designed laser ignition system worked perfectly and reached 100% ignition probability with regard to the operational points derived for potential application in an upper-stage cryogenic expander engine. In addition, margins for the applicability of this laser ignition system were determined and formulated. The OH imaging and dynamic pressure measurements of the ignition process gave a detailed in-sight into the complete ignition process needed to design a full scale application.

The TRP proved that the level of reliability of the laser ignition system for propellant injection conditions in a space environment was significant. Therefore, modification of this LIS in terms of a full scale upper stage engine was strongly recommended. As both ignition concepts (laser-ablation and laser-plasma ignition) proved to be equally reliable but offer different advantages, a set of design options were generated for future applications. Due to the phenomenon of low minimum pulse energy required for reliable ignition and the recent advancements in the field of fiber-based laser pulse transport capabilities, further investigation into fiber-based ignition systems for high thrust engines as well as RCS/OMS was envisaged. This opens up a completely new perspective in ignition system design for multi-engine configurations.

4.1.4.4 CLAWS

Duration: 2016-2018
Partner: DLR Institute of Space Propulsion (project lead); ASL Ottobrunn

Project Description:
The Cyclic Thermal Loading of Actively Cooled Wall Structures (CLAWS) project focusses on achieving the:

- enhancement of an existing phenomenological structural analysis model by adopting the Finite Element integrated damage parameter approach
- extensive validation of this model by a series of TMF tests (high-power, laser-heating) varying:
  - the maximum temperature
  - the laser-on holding time
  - the heat flux.

In order to obtain the highest accuracy rate for validation, the parameters of the material needed for running the structural FE analysis model will be determined by referring to the results of (combined tensile, LCF and creep) material tests with uni-axial samples produced from the same batch of material as the TMF panels. In addition data will be collected of extensive validation measurements (exceeding the selection of options available during the hot run of a combustion chamber) with respect to:

- a highly accurate determination of the local (2d) heat flux distribution by measuring:
  - the total power
  - the 2d power distribution
  - the TMF panel surface absorption of the TMF laser
  - the optical measurement of the 2d temperature field on the laser loaded surface of the TMF panel (by means of an infra-red camera)
- determination of the 2d deformation field of the laser loaded surface (during the complete loading cycle: heating and cooling) of the TMF panel by applying:
  - speckle marks on the laser loaded surface of the TMF panel
  - a stereo camera system
  - image correlation software.

4.1.4.5 Coupling Mechanisms of Combustion and Acoustics in Rocket Combustors

Duration: 2016-2017
Partner: DLR Institute of Space Propulsion

Project Description:
This project resumes the activities of a former TRP study performed in 2011 (see Section 4.1.4.1).

During tests using a subscale combustion chamber supplied by EADS Astrium, a reduction in the fuel injection temperature did not result in combustion instability.

Since that project was finalized DLR has performed additional experiments to investigate the coupling
behavior of its injector setup, which is known to show unstable operation under specific conditions.

Faced with these contradictory data sets it was proposed to approach the problem numerically. Modelling the acoustic behaviour of the two different injector designs will hopefully give an insight into the mechanism causing the DLR combustor instability, and reconcile this with the observations from the Astrium combustor.

The purpose of the current study is to generate test cases describing different types of stability behavior using the data from the former TRP and from the later DLR experiments. The cases should be modelled using the partners’ in-house tools. It will be possible to address the test cases from different depths of detail based on the modelling fidelity of the various approaches used by the partners. Comparing results from these test cases should result in identifying the parameters responsible for the difference in stability behavior of the two combustors. In addition there will be an assessment of the performance of each tool used in modelling the test cases.

**4.1.4.6 Flexible Structures**

Duration: 2009-2016
Partner: DLR Institute of Space Propulsion

Project Description:

During the course of the Flexible Structures project, DLR Lampoldshausen set out to investigate the feasibility of an experimental campaign in a cold wind tunnel facility aiming at characterizing nozzle structure deformation due to flow structure interaction in expansion nozzles. The key requirement for this cold flow test was setting up the fluid structure interaction to correspond with the real application (full-scale engine operated with hot gas).

The following steps were performed:

- literature research
- determining the inner shape of the sub scale nozzle
- optimizing the wall thickness of the sub scale (cold flow) nozzle to achieve ovalization deflection of the sub scale nozzle with a scaling factor (determined by fluid force), which is (although defined as a scalar value) valid for all axial positions of the sub scale nozzle
- a characteristic frequency analysis of the sub scale nozzle after the wall thickness has been optimized
- recommendations were made for the test set-up and data acquisition rates for the sub scale nozzle experiment.

This activity is the first step necessary to give a better insight into the uncertain margins of numerical predictive methods for Fluid Structure Interaction (FSI). The possibility exists to create a database for Computational Fluid Dynamics (CFD) validation for structural models of different complexity based on possible subsequent experiments to be carried out in a follow-up project with the sub scale nozzle with optimized wall thickness. This database can be used for the detailed validation of Fluid Structure Interaction (FSI) solvers. Such solvers are used more and more frequently in space vehicle design and therefore have to be validated in detail and more specifically as regards hypersonic flow. The database should include quantitative uncertainty margins that can only be derived by comparing experimental and numerical results. In addition the database will facilitate an assessment of the validity of the simplified, analytical and empirical models presently available.

**4.1.4.7 Bellows**

Duration: 20015-2016
Partner: DLR Institute of Space Propulsion; FOTEC Forschungs- und Technologietransfer GmbH (in charge of the project); AAC Aerospace & Advanced Composites GmbH

Project Description:

The bellows project is funded by ESA and its main goal is to examine new innovative technologies, and in this case Additive Layer Manufacturing (ALM) as regards its potential use in space craft design and construction.

In order to improve and optimize its characteristics and reduce the risk of malfunction metal bellows were manufactured using the ALM technique with the intention of increasing TRL from one to four. Certain set design rules for ALM where made to investigate in detail the manufacturing limitations, e.g. the orientation of the bellow and the minimum wall thickness. The focus was placed on materials which are currently used for ALM or for space pro-
pulsion hardware. Amongst the first steps taken available literature was evaluated to find suitable materials and the consortium carried out theoretical and experimental assessments. In the final test series, the bellows were screened in terms of verification of quality and performance. This included, for example, carrying out fatigue and pressure tests.

In its role as an expert on material compatibility the Institute of Space Propulsion is providing information and know-how on suitable ALM metals during the project.

Figure 4.04: Additive layer manufactured bellow

4.1.5 Bavarian Technology Projects

4.1.5.1 KonRAT at Ludwig Bölkow Campus

Duration: 2015-2017
Partner: DLR Institute of Space Propulsion
Airbus Safran Launchers GmbH
Technische Universität München
Airbus Defence and Space GmbH
EOS GmbH

Project Description:
The KonRAT project (application of rocket propulsion components for aerospace transport systems) is incorporated in the work carried out by the ‘integrated system’ research group at the Ludwig Bölkow Campus. It is financed by the Bavarian Ministry of Economic Affairs and Media, Energy and Technology to pool expertise and further develop core competencies for rocket propulsion systems in Bavaria. The key objectives are:

− design procedures concerning cryogenic oxygen in connection with turbo pumps
− assessment of selected problems concerning turbo pumps
− additive manufacturing methods for aerospace applications (turbo pump parts and rocket engine valves).

The DLR work package comes under the category of assessing turbo pump problems and covers the aspect of secondary systems. In addition to the main flow path through the inducer and the impeller regarding the pump and the stator and the rotor of the turbine, several additional fluid systems and fluid paths exist in turbo pumps for LRE, e.g. flow through bearings for lubrication, cooling requirements and via the seals as leakage and purge flow. They are all summarized as secondary flow systems and are incorporated into this study.

After a thorough review of the relevant literature, analytical methods were identified and implemented in a program to calculate the forces active inside a turbo pump and the resulting load capacity. The program is used for studying different turbo pump configurations. A more detailed investigation of axial balance systems is being carried out using analytical and numerical tools.

The project will be finalized after inter-propellant seal configurations with and without purge fluid have been studied.

Scientific personnel has been sent to the TU Munich to the Institute of Turbomachinery and Flight Propulsion, Section for Space Propulsion headed by Prof. Haidn to work closely with the KonRAT turbo pump team there and with industrial partners in Bavaria.

4.1.6 DLR Space Management Funded Projects

4.1.6.1 STERN

Duration: 2012-2017
Partner: DLR Space Administration (in charge of the program); DLR Institute of Space Propulsion; DLR Space Operations and Astronaut Training

Project Description:
The DLR Space Agency is in charge of the STERN program (Studentische Experimental-Raketen =
Student Experimental rockets). The agency is financing student groups studying aerospace engineering at 8 German technical universities with a focus on launcher systems. The task for each group is to plan, design and build a rocket with a complete propulsion system, telemetry and recovery system. The goal is to launch their rocket at the Esrange Space Center near Kiruna in the north of Sweden. The DLR Institute of Space Propulsion and the Mobile Rocket Base Department (MORABA) from the DLR Space Operations and Astronaut Training Institute are supervising work and launch campaigns by holding reviews and conducting workshops. At Lampoldshausen M11.5 has been set up as a test field for the students and it is available for carrying out motor test campaigns under the supervision of engineers and scientists from the Institute.

4.1.6.2 EQUAD

Duration: 2016-2017
Partner: DLR Institute of Space Propulsion; Josef Meissner GmbH & Co. KG (project lead)

Project Description:
The acronym EQUAD stands acting for: “Entwicklung und Qualifizierung eines effektiveren und ökonomischeren Herstellungsverfahrens für die grüne Treibstoffkomponente ADN”. The aim of the project is the development and qualification of an efficient and economic production route for the ionic oxidizer ammonium dinitramide (ADN, \([\text{NH}_4]^+ [\text{N(NO}_2)_2]^{-}\)) in connection with orbital propulsion systems. EQUAD aims to develop and test a continuous ADN production procedure under laboratory conditions. The project plan involves the optimization of new fuel formulas taking into consideration the specification standards for orbital propulsion.

Worldwide research and technology development activities are still continuing to find suitable green propellants. For this purpose, the plan is to support activities regarding access to high-quality, accessible and sustainable fuels for satellite propulsion systems also in terms of future economic marketing. The Institute of Space Propulsion is co-developer and provides test facilities. It should be mentioned that research and technology development of ADN-based monopropellants is also being carried out at Lampoldshausen e.g. as part of the EU H2020 project Rheform, see Section 4.1.3.6.

4.1.7 Industry Partner Projects

4.1.7.1 Gel Feeding System Research

Duration: 2012-2017
Partner: DLR Institute of Space Propulsion (in charge of the project); Bayern-Chemie

Project Description:
The objective of this project is to get a deeper understanding of distinct technical gel flow processes related to feeding lines. Bayern-Chemie and DLR provide the funds for a PhD researcher together with the necessary experimental equipment.

Gel propellants are non-Newtonian fluids, i.e. their rheological behavior (shear viscosity vs. shear rate) can be described by the Herschel-Bulkley Extended (HBE) equation which was developed in the last decade as a result of basic research work carried out by DLR. Up to now the level of understanding in technical gel flow processes, e.g. in feeding lines from tank to combustor, was still quite low. For example, pressure loss calculations as described in literature are not much use for this type of non-Newtonian fluid.

This project studies the flow and the pressure loss of gel flows through a short strongly tapered segment of a circular pipe. Figure 4.05 shows a sketch of the experimental setup with the transparent measuring section.

![Figure 4.05: Schematic illustration of the velocity field measurement setup](image-url)
In order to be able to investigate the boundary layer area of the flow the refractive index of the fluid has to be compatible with the materials of the surrounding transparent measuring section. Therefore special gels were developed with an adjustable refractive index, see Figure 4.06.

Figure 4.06: Different gels for optical measurements

4.1.7.2 H₂ ORIZON

Duration: 2014–2017
Partner: DLR Institute of Space Propulsion (heading the project); ZEAG Energie AG

Project Description:
H₂ ORIZON focuses on the construction of a process chain for delivering regenerative hydrogen at the DLR site at Lampoldshausen, including its production, storage, usage and distribution. The set-up resulting from the project will also provide the means of creating heat and electricity via cogeneration. The main components of the process chain are:

- 880 kW PEM electrolyzer system
- 350 bar H₂ dispensing point (tube trailers, cylinder racks).

With its two natural gas-fed CHP plants, whereby one of them can run on CH₄/H₂ mixtures with 0-100 % hydrogen content interacting with the local demands for more use of renewable energy sources, the unique infrastructure of DLR’s site at Lampoldshausen provides ideal conditions to bring Baden-Württemberg closer to a “green” hydrogen economy. Hydrogen is produced via surplus power from a local wind farm. The production and storage in Lampoldshausen significantly shortens the delivery channels for regenerative hydrogen in southern Germany.

Depending on how high the demand is, hydrogen will be used as a propellant for space propulsion tests, as an additional energy source for power and heat for the DLR site and to meet third party requirements such as hydrogen mobility.

The realization of economic and ecological synergy potential between the energy, industry, and mobility sectors is particularly important for a “green” hydrogen economy and the H₂ ORIZON project highlights and promotes this potential. In addition, H₂ ORIZON will investigate how the hydrogen production chain can meet the future needs for a green hydrogen economy.

H₂ ORIZON supports a forward-thinking approach to the development of regional technology competence and is helping to fulfil the objectives of the German Energy Transition.

4.1.7.3 A6 P5.2 Cryogenic Upper Stage Test Facility

Duration: 2015–2018
Partner: ESA
ASL Airbus Safran Launchers
DLR RA P5.2 Project

Project Description:
The Ariane 6 is Europe’s answer to a competitive rocket launch system. DLR has been contracted by ESA to extend the ground testing capacity for the Ariane 6 and building the P5.2 upper stage test platform fulfills this objective.

The project addresses the development, construction and site acceptance of the P5.2 test facility to allow for the hot run testing of the Ariane 6 cryogenic upper stage system (ULPM).

In order to fulfill this objective as economically as possible the P5 test facility is being upgraded to accommodate P5.2. Existing test site hardware resources of P5, of P3.2 and the supply area are being made available for use by the P5.2 facility to keep investment costs to a minimum.

The DLR Institute of Space Propulsion has implemented a project team to facilitate this project, for the most part on the basis of its engineering capabilities and supported by departmental operating resources.

Based on preliminary decisions on the design excavation, work on the P5.2 foundations as per the A5ME processor program commenced in June 2014. The construction phase involving concrete elements was completed in Sept 2015.

Implementation of steel structures and process equipment will be finalized in 2017. In June 2016 the
critical design review was passed on adjustments needed to fulfill ULPM test requirements.

Due to the fact that work on further refining the ULPM design is ongoing, a dedicated final design and implementation effort is planned for 2017. Furthermore, during 2017 and 2018 the P5 platform will operate in parallel during activities involving final inspections and acceptance of the P5.2 construction and testing capabilities. Work on the test facility will ultimately be fully operational in the third quarter of 2018 after a test readiness review.

4.2 Co-operations

4.2.1 National Co-operations

4.2.1.1 Propulsion 2020

Duration: 2011- ongoing
Partner: DLR Institute of Space Propulsion; Airbus DS GmbH

Project Description:

The purpose of the Propulsion 2020 co-operation agreement is to coordinate research and development undertakings carried out by the parties, to supplement activities and to align them with common goals in order to contribute nation-wide to the development of new and improved space propulsion techniques in Europe based on appropriate technologies, processes and materials.

In particular, the research network aims on the one hand at developing a new and improved propulsion system for the Ariane. On the other hand it aims at developing and promoting the use of new technologies in the field of satellite propulsion systems. The results of the research network should be disclosed and later culminate in an industrial application.

Propulsion 2020 is organized under three column headings:

− High Thrust Propulsion
− Satellite Propulsion
− High temperature resistant materials.

The contribution of DLR’s Institute of Space Propulsion comes under High Thrust Propulsion and the following sub-tasks:

− TP 1100 API Injection
− TP 1200 GG/PB-Injection / Laser Ignition
− TP 1500 CFD
− TP 1600 Nozzles
− TP 1700 Combustion Instability
− TP 1800 Life Time Prediction
− TP 1900 Turbo Pumps.

Under the heading of “Satellite Propulsion” the institute of Space Propulsion and Airbus DS handle the following sub-tasks:

− H₂O₂ based propulsion
  - preparative work for the use of H₂O₂ (risk analysis, storage and feeding systems, handling, etc.) in RA-internal project H₂O₂@TRS (funding via ForTrAS / ForTReSS)
  - research and development of mono- and biprop combustor processes (including ambient and vacuum-near ignition)
− Investigation into fluid properties, reactivity and compatibility of advanced propellants
− Technological assessment of various suitable propellants:
  - N₂O based mixtures
  - gels
  - monopropellants
− Providing test facilities to carry out combustion tests on Airbus’ “water propulsion” system.

4.2.1.2 KERS

Duration: 2015- ongoing
Partner: DLR Institute of Space Propulsion; Airbus DS

Project Description:

DLR and Airbus signed a Memorandum of Agreement to cooperate within the framework of KERS (Key Enabling Technologies for Reusable Launcher Systems). Both partners:

− agree that there is a necessity to prepare key enabling technologies for (semi-) re-usability of future launcher systems to increase the competitiveness of the European launcher system by reducing recurring cost.
− affirm that the recent concept on upgrading Ariane 6 which is mainly based on an available liquid propulsion system may be the first step in
attaining a long term objective regarding the more cost efficient development of a partly re usable launcher system.

– agree to combine their abilities and resources to prepare the re-usability of the next generation launcher to the extent of demonstrating key technologies (with Technical Readiness Level (TRL) up to 5/6) since it would constitute an important asset for Europe.

– intend to join forces on an equal basis in terms of facilities, scope and complementary expertise in order to capitalize on synergies in the field of technology development and demonstration capabilities.

– express the desire to work together long-term within the context of the above-mentioned activities.

KERS defines the framework under which DLR and Airbus jointly test the LOX/methane thrust chamber demonstrator at the P3 test bench. In order to carry out this project this particular test facility was modified (see chapter 2.7) to be able to handle Methane testing. DLR contributes by providing hardware, test service, test data and research know-how. ASL submits hardware, test engineering, test articles and design know-how.

After the P3 modifications including run-in tests were carried out, two very successful test series of 10 hot runs each were carried out between September 2015 and October 2016.

Test objectives and achievements are shared with DLR by means of immediate post-test reports including the test data from the ROMEO campaign. The researchers at the Institute of Space Propulsion therefore benefit from the knowledge gained during the tests carried out in a re-usable LOX/methane combustion chamber.

4.2.1.3 TU Kaiserslautern, SAM


Partner: DLR Institute of Space Propulsion
TU Kaiserslautern, SAM

Project Description:

The target of this project is the development of an inducer for a turbo pump in a rocket propulsion system. The project includes the design of state of the art inducers, the CFD validation of various designs (including the performance of the relevant inducers and the limits of cavitation), the manufacturing of validated and selected inducers and the corresponding qualification tests in water. The end product of the tests are performance maps of the inducers showing the rise in pressure versus mass flow for various rotational speeds (including overspeed) and the characteristic cavitation behavior demonstrated by curves showing the increase in pressure versus the net positive suction head (NPSH).

In addition to the inducers developed by TU Kaiserslautern, an inducer provided by Airbus Safran Launcher (ASL) and a further model developed by DLR in Lampoldshausen are being tested in water on the same test rig at TU Kaiserslautern. The inducer provided by DLR was designed by the DLR-Partner Instituto de Aeronáutica e Espaço in Sao Jose dos Campos, Brazil (IAE). This inducer was assembled at DLR-Lampoldshausen as the first section of a five axis numeric milling machine. Work is continuing on the development of turbo milling machine components and this also applies to turbo pump impellers. It was DLR-Lampoldshausen’s task within this project to give advice concerning the design of turbo pump components for cryogenic fluids, to supervise the development and carry out quality assurance. Regular reviews and progress meetings were held with this in mind.

4.2.1.4 Fraunhofer Institute of Chemical Technology (ICT)

Duration: Since several decades up to now, ongoing

Partner: DLR Institute of Space Propulsion; Fraunhofer Institute for Chemical Technology (ICT)

Project Description:

The ICT and the DLR Institute of Space Propulsion have been successfully working together over a very long period so that only the ongoing subjects will be described here.

Both institutes are currently participating in several joint working groups which are only partly listed in this chapter due to confidential restrictions; e.g. the Gel Propulsion Working Group and AG Antriebe.

Within the context of innovative propellants for orbital propulsion ICT is developing new energetic types for mono and bipropellant applications. DLR will be carrying out experiments on such propellants for use in small thrusters. Examples are: ADN- and
H₂O₂-based mixtures, pure energetic ionic liquids without water solvents, etc. A joint patent application has been submitted.

4.2.1.5 Gel Propulsion Working Group / German National Gel Technology Program

Duration: Since 2001, ongoing

Partner: DLR Institute of Space Propulsion (lead); Fraunhofer Institute for Chemical Technology (ICT); Bayern-Chemie; Bundeswehr Technical Center for Weapons and Ammunition WTD91; German Federal Office of Equipment, Information Technology and InöService Support (BAAINBw)

Project Description:

The German Gel Propulsion Technology Program (GGPT) was started in 2001 with the aim to develop within the steps of its first phase the necessary technology to build a gel propellant rocket engine and to demonstrate its capabilities by a demonstration flight within less than a decade. The free-flights of two missiles with a gel rocket motor built by Bayern-Chemie on 9 December 2009 showed the success of this common effort. Focus of the current work within the steps of the GGPT program is the further maturation of the technology, the extension of the range of application and the enhancement of performance and safety.

4.2.2 International Co-operations

4.2.2.1 Construction and Operation of the European Test Bench for Rocket Propulsion

Duration: 1995, ongoing

Partner: DLR Institute of Space Propulsion; CNES; Deutsche Aerospace AG; SEP

Project Description:

The Memorandum of Understanding defines the rules under which P8, the European test bench for high pressure combustion, has been set up and is operated jointly by the partners at the DLR site in Lampoldshausen. In addition to the organizational issues related to the operation of test bench P8 the MoU also provides the framework for the coordination of scientific activities related to high pressure combustion in France and Germany.

4.2.2.2 REST

Duration: 1999 - 2020

Partner: DLR Institute of Space Propulsion; Airbus Safran Launchers, Ottobrunn; Airbus Safran Launchers, Vernon; EM²C, CentralSupelec Paris; CERFACS CNES; CNRS; CORIA, Rouen; Insitute of Fluid Mechanics, Toulouse; ONERA; Technische Universität München;

Project Description:

DLR cooperates on the subject of combustion instabilities in the frame of a MoU with German and French partners from industry, research institutions and agencies (ASL, CentralSupélec Paris, CERFACS, CNES, CNRS, CORIA, IMFT, ONERA, Technical University of Munich). The Rocket Engine Stability Initiative (REST) is working on the common goal of understanding combustion instability phenomena for the benefit of current and future European engine development.

The members meet regularly during scientific workshops and workshops on numerical modelling. Progress on research is exchanged and synergies are sought between the efforts of the numerous partners.

DLR recently provided experimental data for two test cases for the 3rd REST modelling workshop. Test data from combustor H (BKH, Chapter 1.5) was taken for test case HF-6. JAXA, not a REST member, was invited as a guest to take part in this test case. Participants were required to predict system acoustics and recover the flame and LOX jet response to acoustic excitation. The second test case used data from combustor D (BKD, Chapter 1.5). Participants were required to determine which of four load points were stable or unstable, based only on the propellant supply conditions and geometry of BKD.

Several of the participants have continued cooperating on the HF-6 (BKH) and HF-7 (BKD) test cases since the 3rd modelling workshop. Extension of the joint work on the test cases, both from the modelling side as well as the analysis of the experimental data, continues to yield new results which were not conceived of during the original workshop.
### 4.2.2.3 JAXA Research Agreement

**Duration:** 2015-2020  
**Partner:** DLR Institute of Space Propulsion; JAXA  

**Project Description:**  
**Task: High Frequency Combustion Instability in Liquid Rocket Engines**  
The objectives of the cooperation on combustion instability are to benchmark and validate numerical modelling approaches and to exchange findings regarding flame response and driving mechanisms of combustion instabilities.

The main focus of the cooperation in recent times has been the continuation of joint work on the HF-6 test case (see Section 4.2.2.2) based on data from the BKH experiment (Chapter 1.5). JAXA performed further simulations of the experiment with a refined model, and DLR deepened and extended their analysis of the experimental data. This effort has so far yielded several new results and clarifies physical phenomena observed in the experiment. Examples include the approach for comparing acoustic field distributions between experimental and numerical data sets and detailed descriptions of the flame response to transverse acoustic velocity perturbations.

**Task: LOX/Methane Dual-Bell Rocket Nozzle Flow Characteristics**  
A joint test campaign was conducted in 2014 at hot firing test bench P6.1 at DLR Lampoldshausen. Each partner designed and manufactured a dual bell test specimen and they were tested under the same conditions (combustion chamber, instrumentation and test sequence, as far as possible) to compare the design methods. The main objective of the team effort was to produce a transition prediction in hot flow conditions. DLR demonstrated its ability to design and predict the transition of a hot flow dual bell nozzle. Test cases have been defined and are simulated with CFD, using in-house TAU code for DLR and commercial code for JAXA. The methods and results are regularly compared during workshops held with the participation of the cooperating partners. Within the framework of the cooperation activities two partners from JAXA visited DLR during the test phase in early 2014 and a DLR partner (C. Génin) visited JAXA Kakuda in Sept.-Oct. 2014 to discuss the experimental results of the campaign.

**Task: Life Prediction**  
The aim of this JAXA-DLR life prediction co-operation project is to compare the different Finite Element integrated damage parameter analysis methods of JAXA and the DLR Institute of Space Propulsion with respect to their suitability to accurately predict the fatigue life of highly stressed structures in terms of thermal load such as the inner liners of combustion chamber walls, nozzle throats and nozzle extensions. With this in mind the following work was performed during the first part by the JAXA employee Tadashi Masuoka who worked at the DLR institute of Space Propulsion for one year:

- Integration of the JAXA fatigue life analysis model into the commercial Finite Element package used at the Institute of Space propulsion (ANSYS)
- Customization of the parameters of the TMF panel material needed for running the JAXA model (based on the results of uni-axial tensile, LCF and stress relaxation tests with samples made from the TMF panel material)
- Finite element integrated damage parameter analysis of the deformation and the cyclic damage of the DLR TMF panel.

These combined efforts will ultimately produce a fatigue life analysis method for finite elements based on integrated damage parameters. The method takes into account the number of cycles highly stressed structures can take in terms of thermal load before they break up, i.e. either the JAXA method which takes into account as many as three different damage parameter accumulation contributions (kinematic, isotropic and creep) or one of the two (mechanism based / phenomenologically based) damage parameter methods from DLR Lampoldshausen (both containing a large number of isotropic hardening / softening parameters, allowing for a high-end fit of the LCF envelope of uni-axial material tests).

**Task: Film Cooling**  
The joint research on this task focuses on methane film cooling behavior in a GOX/methane combustion chamber. The objectives are to:

- carry out a hot firing test campaign and numerical simulation for methane film cooling in a GOX/methane combustion chamber.
- carry out a hot firing test and obtain validation data for numerical simulation.
- investigate film cooling behavior and its cooling efficiency in a GOX/methane combustion chamber.
− carry out a numerical simulation and validate it against measured data.
− exchange know-how on methane film cooling and its numerical modeling in order to understand physical behavior and obtain accurate prediction.

DLR performs hot firing test campaigns in a GOX/methane combustion chamber with methane film cooling using the test benches at DLR Lampoldshausen. Test data and related technical information are passed on to JAXA.

JAXA carries out numerical simulations for the hot firing tests and provides DLR with computed results and information of numerical modeling.

After all the tasks have been completed a technical workshop will be held during which the obtained experimental and numerical results will be shared.

Hybrid Rockets

Data concerning hybrid rocket propulsion has been exchanged since 2010. A common project proposal on hybrid sounding rocket launcher is in preparation.

4.2.2.4 Chalmers University Gothenburg

Duration: 2015-ongoing
Partner: DLR Institute of Space Propulsion; Chalmers University Gothenburg

Project Description:
The Chalmers University in Gothenburg has profound knowledge in the field of the numerical simulation of nozzle exhaust jets. Based upon joint collaboration within the NOSTER initiative, a research campaign was started to which DLR contributes with its experience in experimental studies. A first joint cold flow test campaign was conducted in 2015 and a second one is planned for 2017.

As a result of the interaction Chalmers gains validation of its numerical methods developed in-house and DLR will build up its competence in the numerical simulation of nozzle exhaust jets.

4.2.2.5 ETH Zürich

Duration: 2016-2018
Partner: DLR Institute of Space Propulsion; ETH Zürich; Technische Universität München;

Project Description:
This cooperation will explore state-of-the-art methods to extract linear growth rates from dynamic pressure measurements. These methods are already applied to unstable gas turbines for the benefit of acoustic damper design. The goal of working together on this subject is to develop a similar capability for rocket engine conditions using BKH and BKH data (Chapter 1.5).

The linear growth rate of thermo-acoustic instability in a practical combustor, such as a gas turbine or rocket engine cannot be obtained directly from measurable pressure signals. This is due to a time-scale difference between localized thermo-acoustic growth and the acoustic response of chamber modes.

Signal processing of dynamic pressure data of both BKD and BKH will be performed to test the applicability of methods currently used in gas turbines. The objective is to extract the linear growth rate of an unstable combustor mode from dynamic pressure data. Knowledge of this growth rate would allow the efficient design of retrofitted acoustic dampers and the scientific validation of linear thermo-acoustic models.

4.2.2.6 University of Texas Austin and NASA MSFC Huntsville

Duration: 2014
Partner: DLR Institute of Space Propulsion; University of Texas Austin; NASA Marshall Space Flight Center, Huntsville

Project Description:
During a team effort with NASA MSFC the University of Texas studied the acoustics of clustered nozzles under transient start-up operation in an SSME and future SLS configuration. Cold flow subscale models were tested under representative conditions at a dedicated test facility in Austin. As DLR has experience in the field of cold flow subscale testing, and the designated SLS configuration with its cryogenic main stage in combination with solid fuel boosters is similar to Ariane 5 and Ariane 6, an exchange of knowledge and personnel was agreed upon. A DLR scientist was assigned to attend the acoustical tests. In return DLR provided and presented its knowledge and experience in designing and testing cold and hot flow dual bell nozzles on site at the Marshall Space Flight Center in Huntsville.
Both sides were satisfied with the results of working together. DLR profited by gaining experience in acoustical measurement methods and the University of Texas and NASA (not only MSFC) got a wide-ranging overview of current dual bell activities as a result of a video conference organized nation-wide.

4.2.2.7 Purdue University

Duration: 2013
Partner: DLR Institute of Space Propulsion

Project Description:
The Head of the Combustion Instabilities Group, Justin Hardi, completed a placement as a visiting scientist at the Zucrow Propulsion Laboratory of Purdue University, Indiana, USA. His tasks included the operation of rocket engine test benches, planning and execution of test campaigns, design and development of new test facilities and experimental rocket combustors, run-in and evaluation of new combustors, data analysis for research objectives, and supervision of graduate and undergraduate students.

The placement was beneficial since there was an exchange of experimental methods and experience. New research results were generated concerning flame-acoustic coupling, heat transfer during combustion instabilities, and the comparison of experimentally measured and numerically modelled flame dynamics.

4.2.2.8 University of Victoria

Duration: 2015-2017
Partner: DLR Institute of Space Propulsion; University of Victoria (Canada)

Project Description:
Interaction between the University of Victoria and the Combustion Instabilities Group focusses on addressing flow induced acoustic resonance in a cold flow experiment representing a common industrial flow system.

The partners are combining analysis techniques to investigate the coupling between vortex shedding and tangential acoustic modes in a resonator cavity. DLR is carrying out calculations to dynamically reconstruct the acoustic field using an algorithm developed to track unsteady rotational modes in rocket combustion chambers with combustion instability. The objective is to establish a connection between the behavior of the acoustic field and the rotational energy measured in the flow field with PIV techniques. This is hoped to reveal the coupling mechanism driving the resonance in the acoustic field.

4.2.2.9 ONERA (MOTAR)

Duration: 2014-2017
Partner: DLR Institute of Space Propulsion; ONERA

Project Description:
Joint activities involving optical diagnostics for combustion instability were carried out during the course of the DLR-ONERA cooperation regarding optical diagnostics in aerospace research (MOTAR).

ONERA participated in an experimental campaign at the P8 test facility with the windowed combustor H (BKH, Chapter 1.5). Equipment and expertise from ONERA were used to enhance the optical diagnostics typically applied in the BKH experiment. This resulted in a significant improvement in the resolution of flame radiation imaging obtained during the application of acoustic perturbations in the BKH combustion chamber.

The partners are both using their own specially developed tools to process the same imaging in different ways, maximising the scientific yield of the data sets. Reciprocal analyses are hoped to reveal more detail on the processes involved in flame-acoustic interaction under conditions representative of dangerous combustion instabilities in a real engine.

4.2.2.10 ESA Technical Assistance

Duration: 2007-ongoing
Partner: DLR Institute of Space Propulsion; ESA

Project Description:
ESA receives technical assistance from DLR research staff as part of the Future Launcher Preparatory Program as follows:

− reviews of relevant documentation
− participation in reviews or other technical meetings as necessary
− critical analysis of the contractor’s logic regarding testing and test objectives
− assessment of P4.1 test campaign logic
assessments of engine test performance related to thermal and functional engineering
- assessment of combustion chamber and igniter performance
- assessment of nozzle operational performance
- assessment of P4.1 test bench performance and especially potential M2-06 anomaly impact
- assessment of the contractor’s logic of test data analysis and conclusions
- development of independent recommendations for future activities.

In 2016 DLR research staff began to provide ESA with technical support also as regards propulsion systems with advanced propellants like green monopropellants, green hypergolic bipropellants, gelled propellants and hybrid rocket propellant combinations. This support includes:
- reviewing relevant literature and documentation
- counselling and assistance regarding decisions on and adaptation of roadmaps
- availability of test positions and laboratory for urgent research tasks at short notice is currently under discussion.

4.2.2.11 Blanching

Duration: 2010 - 2014
Partners: DLR Institute of Space Propulsion; CNES; University Rouen; Submeca Paris

Project Description:

Blanching, as its name suggests, describes the (unintentional) bleaching of a (thermally and chemically highly loaded) metallic material. The reason for this bleaching effect is the reduction of a previously created metal oxide.

A large number of such oxidation and reduction cycles can even cause an increase in thinning and roughness in structures highly stressed in terms of thermal load such as the inner liner of a combustion chamber wall (for highly efficient high thrust engines usually made from a copper base alloy) and might therefore lead to a reduction in the life of the inner liners of chamber walls (from both the remaining copper base alloy geometry and the thermal loading point of view).

The following activities were carried out during the DLR-CNES cooperation on blanching. The work was undertaken by PhD student Hugo Duval, co-financed by CNES and DLR at the premises of SUPMECA Paris and the University of Rouen:
- extensive literature study, 0-dimensional blanching model extraction and a summary of previously performed blanching tests
- creation of a Thermo-Gravimetric Analysis (TGA) blanching test set-up (a highly accurate scale with furnace heating and continuous recording of the weight of the tested samples)
- extensive blanching test series with:
  - oxidizing gas: air (diluted with argon at different mixture ratios)
  - reducing gas: carbon monoxide (diluted with argon)
  - test temperatures: 600°C, 750°C, 900°C
  - blanching cycle length variation: 4 min / 8 min / 12 min
  - tested material samples: made from pure copper (OFHC), CuCrNb and Cu-CrZr
  - oxygen partial pressure variation: 5% / 10% / 15%
  - variation of the ratio of the reduction versus oxidation phase duration: 1:7 / 1:3 / 3:5

The test results provide a broad basis for the validation of surface reaction analysis models. Once established, these models can be used in future for bridging the gap between the TGA test conditions (ambient pressure, duration of the oxidation and reduction phases by the minute) and the conditions in the real-life application (liquid rocket engine - pressures up to 100 bar, oxidation and reduction phases in the range of milliseconds).

4.2.2.12 L75-Turbopump

Duration: 2014-2017
Partner: DLR Institute of Space Propulsion; IAE Instituto de Aeronáutica e Espaço in Sao Jose dos Campos, Brazil; DLR Space Administration; Airbus Safran Launchers GmbH; DLR Engineering Facility

Project Description:
The Brazilian-German joint activities include the development of the L75 liquid propellant (LOX-ethanol) upper stage engine and are organized by the DLR Space Administration. A more in-depth cooperation was agreed upon regarding appropriate turbo pump topics. As a result of this an exchange of knowledge and experience, which is beneficial for both the German and the Brazilian partners, has since been established. On the one hand, the TiR (Turbo pumps in Rocket engines) group at DLR’s Institute of Space Propulsion makes its experience and network information available to industrial and academic partners in the field of turbo pumps. In addition, contact to key suppliers of critical subcomponents e.g. seals and bearings in Germany, is managed by DLR’s Institute of Space Propulsion. On the other hand, IAE provides detailed design solutions and drawings of components and they are responsible for the hardware integration.

An information exchange regarding domestic component tests is taking place. In this context, it should be mentioned that measurement data from inducer tests in water has been generated by the TU Kaiserslautern (see Section 4.2.1.3) with hardware provided by DLR Lampoldshausen and that Airbus Safran Launchers performed accompanying CFD simulations of the water tests on the LOX pump at IAE. The results gained are used for cross checking and validation work.

Based on the L75 turbo pump design, DLR has been looking into alternative manufacturing methods for the LOX impeller, including innovative additive manufacturing approaches. The DLR Engineering Facility could prove that this process could be used to build complex parts in one piece using additive manufacturing. For this reason changes in the design of the impeller were necessary. However three different impellers adapted from the IAE baseline design are being examined in terms of their manufacturing precision. Spin tests carried out by a specialized German company are designated to evaluate the structural integrity of the parts.

DLR Lampoldshausen is providing support for preliminary plans and contacts to engineering companies in Germany for the construction of a seal bearing shaft test facility at IAE and investigating the possibility of subcomponents tests to be carried out by the supplier.

These cooperation activities, with regular web-conferences, workshops, and lean management are proving successful as a driving force in moving the L75 turbo pump project forward towards its goal of creating a basic integrated turbo pump assembly as a pre-development model due mid 2017.

In future and in particular with regard to the next phase of the L75 project, power pack tests at P8 and the new P8.3 at DLR Lampoldshausen are planned. An exchange of scientific staff could further reinforce the cooperation.

4.2.2.13 Test Facility P8.3

Duration: 2016-2019
Partner: DLR Institute of Space Propulsion, CNES, ASL

Project Description:
The DLR P8 cryogenic test facility with its test cells P8.1 and P8.2 is a high pressure test facility for research and development of rocket engine components with the exception of turbo pumps which need a low pressure supply.

The P8.3, a new test cell with a low pressure cryogenic supply has to be erected in order to be able to test turbo pumps and engines driven by turbo pumps. The P8.3 test cell will have similar properties as the other test cells (media supply, mass flow, maximum thrust). It will make use of as much of the P8 infrastructure as possible (storage tanks and MCC).

4.2.2.14 FHWN (University of Applied Sciences Wiener Neustadt) and FOTEC

Duration: Since 2008, ongoing
Partner: DLR Institute of Space Propulsion; FOTeC; FHWN

Project Description:
The Institute of Space Propulsion is working together with FHWN, the University of Applied Sciences Wiener Neustadt and FOTEC, a research company associated to FHWN on the GRASP, Bellows and Rheform projects. Opportunities for working on further joint projects are under regular discussion.

4.2.2.15 FOI

Duration: 2008 - ongoing
Partner: DLR Institute of Space Propulsion; FOI

Project Description:
The Institute of Space Propulsion pools its resources with FOI, the Swedish Defence Research Agency in the GRASP and Rheform projects. The option of working together on further projects comes up during discussions on a regular basis. For example, a common proposal for a H2020 project on green bipeppellants, called HELP was submitted in 2015.

4.2.2.16 Politecnico di Milano

Duration: Since decades, ongoing
Partner: DLR Institute of Space Propulsion; Politecnico di Milano (Polimi), Dept. of Aerospace Science and Technology

Project Description:
DLR has been working together with Polimi on a successful basis over a long period. Only current research activities will therefore be described here, e.g.:

- The analysis of new energetic materials with a view to their suitability for propulsion applications. For example joint activities were carried out on the development and testing of paraffin based solid fuels for hybrid rocket motors. Results of this common work got the 2015 AIAA Best Hybrid Paper Award.
- lecture contributions both at Polimi and University of Stuttgart
- an exchange of students for internships, bachelor and master thesis projects.

4.2.2.17 Pennsylvania State University

Duration: Since 1990
Partner: DLR Institute of Space Propulsion; Pennsylvania State University, USA;

Project Description:
With the Penn State University exists a long-term collaboration. This covers

- exchange of information on combustor processes with liquid, gelled, hybrid and solid propellants
- associate editor of the International Journal of Energetic Materials and Chemical Propulsion (H. Ciezki)
- organization of ISICP conferences
- Host: 2-ISICP 1990; 11-ISICP 2017, 12-ISICP 2018 or 2019 (tbd)
- scientific board membership at many ISICP conferences
- lecture contributions.
5. DLR_Campus
Lampoldshausen

5.1 Scientific and Technical Education

Helping to develop the next generation of scientists is a top priority at DLR. This is accomplished by means of various activities brought together and carried out as part of an integrated concept under the name of DLR_Campus. This approach is designed to help encourage the curiosity and increase the interest of new talents to follow a scientific career. DLR_Campus addresses the different target groups by offering appropriate training exercises at various stages along the entire route of their academic education and is divided into two main fields of activity:

DLR operates student labs called DLR_School_Labs at various sites in Germany giving young people an initial impulse to study a DLR related topic, for example, at university. Special efforts are made to encourage more girls and young women into taking an active role in the scientific world. The DLR_School_Labs pay particular attention to this aspect and take it very seriously not only during the annual Girls’ Day, but also on a day-to-day basis.

A special program called DLR_Talent_School addresses a select group of highly gifted students. These workshops cover several days and are intended to give the participants a deeper insight into the work of DLR institutes and the career paths available.

DLR_School_Labs also offer student traineeships at the various DLR locations. Internet resources for children and young people, informative hand-outs for schools and student competitions complement this DLR portfolio as well as special events and exhibitions at, for example, the International Aeronautical Congress.

Activities relevant for university students and postgraduates are combined under the heading DLR_Academic_Lab. At any one time the DLR...
Institutes supervise several students, either in traineeships lasting a number of weeks or long-term during the practical portion of their thesis projects. Students are also invited to attend various high-caliber informative events like DLR_Student_Workshops or DLR_Summer_Schools at individual DLR locations. To round off the thematic aspect of their graduate work the DLR_Graduate_Program offers its postgraduate staff additional top-quality training sessions to improve their soft-skill qualifications.

5.2 The DLR_School_Lab

The DLR was one of the first German research institutions to set up a student lab. The first DLR_School_Lab began operations in Göttingen in the year 2000. Since then a total of twelve DLR_School_Labs based at various DLR locations or partner universities have opened their doors to welcome and coach more than 36,000 students on an annual basis.

![Figure 5.04: Number of Students visiting the Lampoldshausen/Stuttgart DLR_School_Lab since 2011 (as at 31.10.2016).](image)

The DLR_School_Lab Lampoldshausen/Stuttgart was founded in 2005 and is located at the DLR site in Lampoldshausen. At first it offered courses for high school students and nowadays also holds several experimental workshops all based on three factors that represent the main concept of the DLR_School_Labs:

- **Fascination:**
  Europe's most powerful rocket, a large airplane carrying a heavy IR-telescope weighing 17 tons or a water droplet that seems to stand still in front of your nose - all these are topics which can 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 dig deeper also into other areas of scientific research.

- **Authenticity:**
  The laboratory is located at the center of the DLR test site. Thus the students can work in the inspiring and authentic atmosphere of the DLR test site like the real scientists. They work on “sub-scaled” experiments with real scientific equipment that is not generally available in schools. The DLR_School_Lab offers experimental learning methods close to current research in the authentic environment of the Institute's test site.

- **Hand-on experiments:**
  The most important part of the concept is experimentation: the students carry out experiments by themselves. They perform their “research” together with real scientific or technical staff from the DLR in small groups (4-5 students) and thus get hands-on experience in science and technology. They therefore gain an authentic impression about how science works.

![Figure 5.05: DLR-Forum of Space Propulsion](image)

In 2009 to satisfy the increasing demand for activities for middle school students the DLR_School_Lab concept widened its range of experiments to attract younger students between the ages of 12-15 years old. In 2013 the student laboratories of the DLR_School_Lab at the DLR site in Lampoldshausen
moved to a new building, the “DLR-Forum of Space Propulsion”.

In addition to the students’ laboratories also the “Space Propulsion Exhibition” as described in 5.4 moved to the Forum of Space Propulsion so that it can be visited by school classes attending the DLR_School_Lab. A lecture room and conference rooms are included in this building. The Forum is therefore a great place for DLR educational activities and demonstrates the extensive effort that the DLR puts into inspiring young people at the DLR site at Lampoldshausen. Since 2015 the DLR_School_Lab Lampoldshausen/Stuttgart even offers special events for primary school and pre-school kids. The DLR_School_Lab thus has a role in the “Tag der kleinen Forscher” (Little Scientists’ Day).

### Figure 5.07: Class level distribution of students visiting the Lampoldshausen/Stuttgart DLR_School_Lab (as of 31.10.2016).

During the “regular lab visits” the Lampoldshausen/Stuttgart DLR_School_Lab enables students to experience the fascination of research. Here the focus is on conducting hands-on experiments tailored to meet the requirements of the respective age group. Each DLR_School_Lab reflects the thematic specialization of the institutes and facilities of the host location. Selected topics similar to those currently under research at the DLR test site at Stuttgart are also represented in the lab in Lampoldshausen. In total the DLR_School_Lab Lampoldshausen/Stuttgart can offer experimentation in up to 11 different fields:

- Vacuum technology – High altitude simulation
- Combustion and Combustion instability
- Optical Measurement
- Rocket flight
- Satellite navigation
- Aerodynamics
- Microgravity
- Fuel Cell
- Solar Cell
- Grätzel Cell (dye-sensitized solar cell)
- SOFIA.

### Figure 5.08: Hands-on: girls performing an experiment on combustion.

New experimental areas in preparation are:

- Hydrogen as a storage medium for renewable energy
- Earth observation
- Test stand for water rockets.

All experiments have a modular structure, where the level of difficulty and the duration can be modified. They are tackled independently by small teams of max. five students supervised by DLR staff and university student tutors who have the required didactic training and are familiar with the topics of the various experiments.
The DLR_School_Lab concept focuses particularly on attracting participants from the target group of girls and young women with the aim of inspiring them to consider later taking up a career in science and technology. Special events to help achieve this goal include the annual “Girls’ Day” but the DLR_School_Lab also aims to attract the attention of female participants at all stages during its program on a daily basis. The Girls’ Day takes place once a year nationwide and the continual interest in this event is more than encouraging.

Figure 5.09: Students feedback in 2015 on the question: “How do you like the DLR_School_Lab?” (left diagram) and “Has the visit of the DLR_School_Lab increased your interests in science?” (right diagram)

Figure 5.10: Girls testing their self-made Graetzel-solar-cells.

Although the DLR_School_Lab routine is designed to attract the general public, there are also special programs for selected highly gifted young people. The workshop lasts for several days and runs under the title DLR_Talent_School. The goal is to give the participants a deeper insight into the work of the DLR Institute of Space Propulsion. For example one of these DLR_Talent_Schools is an annual one week visit of highly gifted students from the Landesgymnasium für Hochbegabte Schwäbisch Gmünd. The program of this visit contains extended hands-on experiments from the selection on offer by the DLR_School_Lab, lectures about space propulsion and a micro rocket workshop.

Figure 5.11: Students building a mirco launcher.

The DLR_School_Lab acts as the main point of contact as regards student internships at the DLR Institute of Space Propulsion, thus building on the programs already available in the students’ laboratory and taking candidates a step further. A special type of internship in Baden-Württemberg lasts a week and takes place during the school term, the so called BOGY internship (Berufsforientierung an Gymnasien). In 2016 the DLR_School_Lab was able to offer internships to 47 school students in the DLR Institute of Space Propulsion. And last but not least the DLR_School_Lab Lampoldshausen/ Stuttgart organizes workshops for teachers to provide background information on the current status of research and to suggest ideas on how to make the presentation of science and technology subjects in the classroom more attractive.

Figure 5.12: Development of the proportion of female participants since 2011 in the DLR_School_Lab Lampoldshausen/Stuttgart

Figure 5.11: Students building a mirco launcher.
Since 2011 the Lampoldshausen/Stuttgart DLR_School_Lab has also initiated or taken part in more than 100 special events and exhibitions for the public and particularly for children. Such sessions range from local and national activities like the open day and events aimed at increasing the awareness of something sensational in the world of science like the Rosetta mission or the launch of Alexander Gerst to the ISS, to presentations on an international level like at the International Astronautical Congress 2014 in Toronto.

The DLR_Academic_Lab

The second column of the DLR_Campus model is the DLR_Academic_Lab providing numerous opportunities for university students and postgraduates. Its main features are the DLR_Summer_School, DLR_Student_Workshops and the DLR_Graduate_Program.

The DLR_Academic_Lab in Lampoldshausen started in 2011 with the first DLR_Summer_School Space Propulsion addressing 20 students from aerospace faculties all over Germany. The participants therefore have an elementary knowledge of rocket propulsion and the subject matter is not new to them. Once a year for two weeks the DLR_Summer_School provides a condensed presentation of the current state of research with lectures given by internal and external specialists and workshops including practical exercises for participants. The DLR_Summer_School session covers about 30 lectures which build on the knowledge and skills taught at university as regards propulsion technologies. The lectures have a special focus on specific European aspects of space transportation, interdependency of system components, political and industrial context of space transport and the current state of research. The speakers therefore come from various European institutions in the aerospace sector like, for example, ESA, CNES, ASL or DLR. The themes of the lectures are categorized by six modules:

- Module 1: missions and applications: e.g.: mission requirements, mission analysis and launcher requirements.
- Module 2: launchers: e.g.: Ariane 6 and the Future Launcher Preparatory Program.
- Module 3: stages: e.g.: upper stage technology, light weight structures and propellant management.
- Module 4: propulsion: e.g.: Vinci, advanced propellants, satellite propulsion, combustion modelling and combustion instabilities.
- Module 5: test- und launch facilities: e.g.: Test as you fly - fly as you test, high altitude testing technologies, testing of rocket stages, risk analysis and risk management at test facilities.
- Module 6: applications: e.g.: planetary missions, earth observation, micro-satellites and Galileo navigation methodology.
Practical hands-on workshops are also part of the DLR_Summer_School. These workshops held with small groups of participants are planned in such a way that the students have to put to test knowledge they have gained during their lectures and work in teams to complete practical laboratory exercises and engineering projects. Typical themes of these workshops are for example modeling a hybrid motor, testing a hybrid motor, optical diagnostics, risk analysis, acoustics in combustion chambers and supply systems.

To improve the practical training of university students the Lampoldshausen DLR_Campus developed a test bench for solid and hybrid rocket engines. This test bench provides students with the entire processes and facilities of a professional propulsion test bench.

Another section of the DLR_Academic_Lab involves DLR_Student_Workshops and in particular the DLR_STERN_Workshops. These events usually last for three days during which the participants can get a deeper insight into special topics in the field of space propulsion. The DLR_STERN_Workshops are special training sessions conducted for the participants of the STERN program (Chapter 4.1.6.4) which is headed by the DLR Space Agency. In three DLR_STERN_Workshops risk analysis and operational safety management for test activities, building and handling of rocket test benches, testing and development of rocket engines are covered.

During all these events there is also enough time for students to talk amongst themselves and with DLR representatives, for example also concerning on-the-job training or career options. Self-evaluation and participant feedback guarantee that these events undergo continuous further development and improvement.

Exhibition

In June 2013 the DLR Institute of Space Propulsion opened the DLR-Forum of Space Propulsion, which puts people in direct contact with the history of European astronautics and current relevant research topics such as laser ignition systems usable in space propulsion engines and regenerative cooled combustion chambers manufactured by Additive Layer Manufacturing (ALM). Numerous exhibits illustrate the site’s outstanding competence in particular in the development of high-altitude simulation facilities and rocket engine tests. Experts, professionals, researchers from other research institutes but also students, pupils and interested visitors are thus able to increase their knowledge on aerospace topics.

Since the DLR opened the exhibition approximately 13,000 visitors from Baden-Württemberg, Germany
and Europe have come to Lampoldshausen. National and international partners are invited to use the DLR-Forum with its open-spaced and modern styled exhibition area as a communication platform with scope for creativity. Three meeting rooms are available for holding research conferences, congresses and events to encourage know-how transfer.

![Figure 5.19: DLR expert explaining steam-generators to young people in the exhibition of the DLR-Forum of Space Propulsion.](image)

All in all the DLR_Campus concept exceeds its goal in paving the way towards increasing awareness of science and technology. By planting initial seeds of interest it continues to make a huge contribution to building on the foundation of knowledge for future generations.
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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>AIAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
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<tr>
<td>A5</td>
<td>Ariane 5</td>
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<tr>
<td>A5 ME</td>
<td>Ariane 5 Midlife Evolution</td>
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<tr>
<td>A6</td>
<td>Ariane 6</td>
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<td>AAS</td>
<td>Advanced Altitude Simulation</td>
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<td>ADN</td>
<td>Ammonium Dinitramide</td>
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<td>AESTUS</td>
<td>Engine of Ariane's EPS Upper Stage</td>
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<td>AG</td>
<td>Arbeitsgruppe (team)</td>
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<td>ALD</td>
<td>Air Liquide Germany</td>
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<td>ALM</td>
<td>Additive Layer Manufacturing</td>
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<td>API</td>
<td>Advanced Porous Injector</td>
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<td>ARA</td>
<td>Nano Colour Coating</td>
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<td>Ariane 5 Research and Technology Accompaniment</td>
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<td>ATV</td>
<td>Automated Transfer Vehicle</td>
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<td>BFF</td>
<td>Black Flow Frosting</td>
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<td>DLR - Institute of Structures and Design</td>
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<td>BK(2)</td>
<td>Brennkammer (Thrust Chamber)</td>
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<tr>
<td>BOGY</td>
<td>Berufserziehung an Gymnasien (scholar internship)</td>
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<td>BS OHSAS</td>
<td>British Standard Occupational Health and Safety Assessment System</td>
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<tr>
<td>C/C-SiC</td>
<td>Carbon/Carbon Silicon Carbide (Ceramic Composite)</td>
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<td>C₃H₆</td>
<td>Cyclopropane (Trimethylene)</td>
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<td>C₃H₈</td>
<td>Propane</td>
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<td>Calorimetric</td>
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<td>Cost Design Review</td>
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<td>Chemical Equilibrum with Application</td>
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<td>CERFACS</td>
<td>Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>Methane</td>
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<td>Ethene</td>
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<td>CM</td>
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<td>CNES</td>
<td>Centre National d'Etudes Spatiales (French Space Agency)</td>
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<td>CNRS</td>
<td>Centre National de la Recherche Scientifique</td>
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<td>CORIA</td>
<td>Complexe de Recherche Interprofessionnel en Aérothermochimie</td>
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<td>Common Research Chamber</td>
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<tr>
<td>CRE</td>
<td>Compte-rendu d’essai</td>
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<tr>
<td>DDS</td>
<td>Data Distribution and Storage</td>
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<td>DFG</td>
<td>Deutsche Forschungsgemeinschaft (German Research Foundation)</td>
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<tr>
<td>DIN</td>
<td>Deutsche Industrie Norm (German Industry Norm)</td>
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<tr>
<td>DMA</td>
<td>Direct Memory Access</td>
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<tr>
<td>DoF</td>
<td>Degree of Freedom</td>
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<tr>
<td>EADS</td>
<td>European Aeronautic Defence and Space Company</td>
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<tr>
<td>ECAPS</td>
<td>Enterprise Coordination and Approval Processing System</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>EIL</td>
<td>Energetic Ionic Liquid</td>
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<td>ELDO</td>
<td>European Launcher Development Organisation</td>
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<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
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<td>EMI (2)</td>
<td>Ernst-Mach-Institute</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 Propellants Stockables (Storable Propellant Stage)</td>
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<td>EQUAD</td>
<td>Development and Qualification for ADN</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>ESPSS</td>
<td>European Space Propulsion System Simulation</td>
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<td>ESS</td>
<td>Emergency Stop System</td>
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<td>ETID</td>
<td>Expander Technology Integrated Demonstrator</td>
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<td>FHWN</td>
<td>Fachhochschule Wiener Neustadt (University Wiener Neustadt)</td>
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<td>FLACS</td>
<td>Flame Acceleration Simulator</td>
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<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>Swedish Defence Research Agency</td>
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<td>FOLAN</td>
<td>Forschung für Lagerfähige Antriebe (Research for Storable Propellants)</td>
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<td>ForTrAS/ ForTReSS</td>
<td>Fortschrittliche Treibstoffe für den Satelliten und Stufenbereich (Advanced Propellants)</td>
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<td>FOS</td>
<td>Forschungsverbund Oberstufe (Upper Stage Research Network)</td>
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<td>FOTEC</td>
<td>Forschungs- und Technologietransfer GmbH</td>
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<td>FSS</td>
<td>Free Shock Separation</td>
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<tr>
<td>GCH₄</td>
<td>Gaseous Methane</td>
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<td>Gaseous Helium</td>
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<td>German Gel Propulsion Technology Program</td>
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<td>GH₂</td>
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<td>GN₂</td>
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<td>H₂</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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<td>HTPB</td>
<td>Hydroxyl Terminated Polybutadiene</td>
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<td>HyNOx</td>
<td>Hydrocarbons mixed with Nitrous Oxide</td>
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<td>ICA</td>
<td>Independent Component Analysis</td>
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<td>IMFT</td>
<td>Institut de Mécanique des Fluides de Toulouse</td>
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<td>IMH</td>
<td>Integrated Management Handbook</td>
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<td>Integrated Management System</td>
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<td>IR</td>
<td>Infrared</td>
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<td>ISO</td>
<td>International Organisation for Standardisation</td>
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<td>ITEM-FK</td>
<td>Innovative Technologies and Methods for Missiles</td>
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<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
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<td>LCF</td>
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<td>LEAP</td>
<td>Launchers Exploitation Accompaniment Program</td>
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<td>LES</td>
<td>Large Eddy Simulation</td>
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<td>LF</td>
<td>Low Frequency</td>
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<td>LH₂</td>
<td>Liquid Hydrogen</td>
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<td>LiBS</td>
<td>Laser-Induced GAS-Breakdown Spectroscopy</td>
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<tr>
<td>LIF</td>
<td>Laser-Induced Fluorescence</td>
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<tr>
<td>LIS</td>
<td>Laser Ignition System</td>
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</table>
LMD  Laser Metal Deposition
LMP-103S  Liquid Monopropellant 103S
LNG  Liquefied Natural Gas
LOX  Liquid Oxygen
LUMEN  Liquid Upper Stage Demonstrator Engine
MASCOTTE  Montage Autonome Simplifié pour la Cryocombustion dans l'Oxygène et Toutes Techniques Expérimentales
MCC  Measurement, Command and Control
MCO  Maintien en Condition Opérationnelle
MMF  Monomethylformamide
MMH  Monomethylhydrazine
MON  Mixed Oxides of Nitrogen
MoU  Memorandum of Understanding
MTBF  Mean Time before Failure
MTBR  Mean Time between Removals
MTTB  Mean Time to Breakdown
N₂O  Dinitrogen Monoxide
N₂O₄  Dinitrogen Tetroxide
NASA  National Aeronautics and Space Administration
NASTRAN  Nasa Structural Analysis System
NCR  Non-Conformance Report
Nd:YAG  Neodymium-doped Yttrium Aluminium Garnet (Laser)
NICEMS  Non Ionic Combustible Energetic Materials
NOFBX  Nitrous Oxide fuel blend
NPR  Nozzle Pressure Ratio
NTO  Dinitrogen Tetroxide
O₂  Oxygen
OH  Hydroxyl Radical
OMS  Orbital Maneuvering System
ONERA  Office National d'Études et de Recherches Aéronautiques
PAL  Propulseurs d'Appoint à Liquides
PDR  Preliminary Design Review
PIV  Particle Image Velocimetry
POD  Proper Orthogonal Decomposition
PPH  Poudre-Poudre-Hydrogène
ProTAU  Rocket Propulsion in TAU
PSD  Power Spectral Density
PTE  Prüfstandtechnologie (Engineering Department)
q2D  quasi two-dimensional
RA  DLR-Institute of Space Propulsion
RAID  Redundant Array of Independent Disks
RBCC  Rocket-Based Combine Cycle
RCS  Reaction Control System
REACH  Registration, Evaluation, Authorization and Restriction of Chemicals
REST  Rocket Engine Stability Research Initiative
RFQ  Request for Quotation
RFR  Raketenstufe für Forschungsraketen (Rocket stage for research rockets)
RHEFORM  Replacement of hydrazine for orbital and launcher propulsion systems
RLV  Reusable Launch Vehicle
RMS  Root Mean Square
ROF  Ratio Oxynitride Fuel
RP-1  Rocket Propellant 1
RSS  Restricted Shock Separation
SCC  Stress Corrosion Cracking
SCORE-D  Staged Combustion Rocket Engine Demonstrator
SeLEC  Selective Laser Melting for Engine Components
SEP  Société Européenne de Propulsion
<table>
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<th>Abbreviation</th>
<th>Description</th>
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<td>SILA</td>
<td>Side Loads and Acoustics in Rocket Engines at DLR Lampoldshausen Test Benches</td>
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<tr>
<td>SFB</td>
<td>Sonderforschungsbereich (Collaborative Research Center)</td>
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<td>SFB-TR</td>
<td>Sonderforschungsbereich TransRegio (Collaborative Research Center TransRegio)</td>
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<tr>
<td>SLM</td>
<td>Selective Laser Melting</td>
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<tr>
<td>SLRD</td>
<td>Side Load Reduction Device</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>SoWarLa</td>
<td>Solare Wasserreinigung Lampoldshausen (Solar Water Cleaning)</td>
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<td>SST</td>
<td>Stage Simulation Tank</td>
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<tr>
<td>TAU</td>
<td>DLR Inhouse CFD Tool (Proper Name)</td>
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<tr>
<td>TAUROS</td>
<td>TAU for Rocket Thrust Chamber Simulation</td>
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<tr>
<td>TCP/IP</td>
<td>Transmission Control Protocol / Internet Protocol</td>
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<tr>
<td>TD-B</td>
<td>Technology Demonstrator B (Ge)</td>
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<tr>
<td>THETA</td>
<td>Turbulent Heat Release Extension of the TAU-Code</td>
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<tr>
<td>TIC</td>
<td>Truncated Ideal Contour</td>
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<td>TMF</td>
<td>Thermomechanical Fatigue</td>
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<tr>
<td>TNT</td>
<td>Trinitrotoluene</td>
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<tr>
<td>TOSCA-TS</td>
<td>Trajectory Optimization and Simulation of Conventional and Advanced Transport Systems</td>
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<td>TRP</td>
<td>Technology Research Program</td>
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<td>TTZ</td>
<td>Technology Transfer Center Lampoldshausen</td>
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<td>UDMH</td>
<td>Unsymmetrical dimethylhydrazine</td>
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<tr>
<td>UMS</td>
<td>Utility Management System</td>
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<tr>
<td>UVV</td>
<td>Unfallverhütungsvorschriften (regulations to prevent accidents)</td>
</tr>
<tr>
<td>VEA</td>
<td>Department Test Facilities (Versuchsanlagen)</td>
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<tr>
<td>VINCI</td>
<td>Ariane new upper stage engine</td>
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<td>VPS</td>
<td>Vacuum Plasma Spraying</td>
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<td>VULCAIN</td>
<td>Ariane main stage engine</td>
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<td>WON</td>
<td>Work Order Number</td>
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<td>WSA</td>
<td>Heat flux transducer</td>
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<td>X-TRAS</td>
<td>Expertise Space Transport Systems</td>
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</tbody>
</table>
Refereed Publications

2011


2013


Status Report 2011-2017


2014


[2015]


AEROSPACE SCIENCES (EUCASS), 29 June – 03 July 2015, Krakau, Polen.


2016


Books, Book Chapters, Journals

2011


2012


2013


2014


2015


2016
Conference Contributions

2011


[31] Sender, J. (2011) LAPCAT II, D5.3.3: Results of M3.1 Gas Generator Test Campaign. Projektbericht.


2012


2013


2014


European Research Program ATLLAS2. 19th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 16 – 20 June 2014, Atlanta, USA.


2015


Conference for Aerospace Sciences - EUCASS, 29 June – 03 July 2015, Krakow, Poland.


2016


Proceedings. Space Propulsion 2016, 02 – 06
May 2016, Rome, Italy.

**Patents**

**2011**


**2012**


**2013**


**2014**


**2015**


Institute of Space Propulsion Documentation

Status Report 2011-2017


Institute Seminars

2011

High Frequency Combustion Instabilities: Coupling Mechanisms in LOX/CH₄ Spray Flames
M. Sliphorst, DLR Lampoldshausen

Verification, Validation and Testing of Kinetic Models of Hydrogen Combustion in Fluid Dynamic Computations
Dr. V. Zhukov, DLR Lampoldshausen

Thickness modulation of micron sized liquid sheets: Generation and quantitative analysis
Dr. P. Steffen, Max-Planck-Institut für Dynamik und Selbstorganisation

What do Scramjets and Kangaroos have in common?
S. Beinke, DLR / The University of Adelaide

CFD simulation of the ignition of coaxial injected methane and oxygen
M. Wohlhüter, DLR Lampoldshausen

Impact of injection distribution on cryogenic rocket engine stability
J. Deeken, DLR Lampoldshausen

Numerische Untersuchung des heißgas- und kühlmittelseitigen Wandwärmeübergangs in konvektiv gekühlten Düsenweiterungen von Flüssigkeitstreibstoff-Raketentriebwerken
L. Werling, DLR / Universität Karlsruhe

Experimentelle und numerische Untersuchung von Wärmestrom in Dual-Bell Düsen

2012

CFD simulations of Flow in Combustion Chambers with Porous Injector Head
Dr. V. Zhukov, DLR Lampoldshausen

Rigid Body 3D Motion Tracking using a Single Viewpoint
M. Wittal, DLR / Hochschule Heilbronn

Hydrodynamische Instabilitäten in dünnen Flüssigkeitsfilmen
Hydrodynamic instabilities in thin fluid films
Prof. Dr. M. Bestehorn, BTU Cottbus

Comparison of like - on - like doublet and triple impinging jet injectors
P. Dilucca, DLR / Politecnico Di Milano

Lattice Boltzmann Simulation
T. Traudt, DLR Lampoldshausen

Europas Weltraumbahnhof Guyana: Eine Startbasis, 3 Trägersysteme
R. Schürmanns, DLR Lampoldshausen

Characterization of thread-like structures formation during the injection of polymer based liquids with a like-on-like impinging injector
M. Redaelli, DLR / Politecnico di Milano

Rocket Combustion Research at Purdue University
Prof. W. Anderson, Purdue University

Weltraummüll
Prof. M. Oschwald, DLR Lampoldshausen

Untersuchungen der Dämpfungsverhältnisse eines Lambda/4-Absorbers mit Rippen
### Status Report 2011-2017

**S. Graf, DLR / Universität Stuttgart**  
*Auslegung und Konstruktion einer Hochdruck-Raketenschubkammer für die Treibstoffkombination Wasserstoff/Sauerstoff*

**G. Kühlwein, DLR / Universität Stuttgart**  
*High Performance Green Propulsion for Space Applications*

**K. Anflo, ECAPS AB, Sweden**  
*Mixing in Shear Coaxial Jets*

**Dr. I. Leyva, AFRL (Air Force Research Lab), U.S.A.**  
*Combustion Modeling at DLR-Lampoldshausen: Nov 2007 - Nov 2012*

**Dr. V. Zhukov, DLR Lampoldshausen**  
*Permeability properties of a C/C media*

**L. Brocard, Arts et Métiers Paris Tech, France**  
*2013*

**G. L. Somma, DLR / Università die Roma**  
*Numerical Simulation of Fluid Transient Phenomena at Test bench M3.5*

**M. Wittal, DLR / Hochschule Heilbronn**  
*Dynamic Two-View 3D Motion Tracking*

**H. Duval, SUPMECA, Paris, France**  
*Experimental investigation and numerical modeling of blanching effects of typical rocket combustion chamber wall materials*

**M. Vargas Nettelnstroth, DLR / RWTH Aachen**  
*Projekt ProTAU - Eine Übersicht für Mitarbeiter*

**B. Wagner, DLR Lampoldshausen**  
*2014*

**H. Kawashima, JAXA, Japan**  
*Introduction of myself and Japanese new engine/launcher*

**M. Hülssiep, DLR / Universität Stuttgart**  
*CFD Modelling of Cryogenic Injection at Supercritical Pressure*

**L. Selle, Institute of Fluid Mechanics, Toulouse, France**  
*Stability-Rating am DLR – ein Konzeptvergleich*

**M. Binnig, EADS Astrium / Universität Stuttgart**  
*Untersuchung eines Helium Heizkonzeptes auf dem Ariane 5 ECA Träger*

**L. Taules, T. Jäger, Airbus DS, Lampoldshausen**  
*Upper stage propulsion system simulation*

**Prof. M. Tanabe, Nihon University, Japan**  
*Charakterisierung und Design-Optimierung eines Formgedächtnis-Ventils*

**S. Schulze, DLR / Universität Stuttgart**  
*Vorbereitung einer Testposition und Testkampagne für eine Turbopumpe eines Rakentriebwerks mit kryogener Flüssigkeit*
<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Institution(s)</th>
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<tbody>
<tr>
<td>Auslegung, Fertigung und Prüfung einer keramischen Modellschubkammer für ein Hybridraketentriebwerk</td>
<td>H. Seiler, DLR / Universität Stuttgart</td>
<td></td>
</tr>
<tr>
<td>Modellierung eines Injektionssystems einer Raketenbrennkammer unter akustischer Anregung</td>
<td>G. Babij, DLR / Universität Stuttgart</td>
<td></td>
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<tr>
<td>Arianespace</td>
<td>H. Zeller, Arianespace / France</td>
<td></td>
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<td>Space Debris</td>
<td>C. Bonnal, CNES / France</td>
<td></td>
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<td>Ariane 5ME</td>
<td>R. Albat, ESA / France</td>
<td></td>
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<tr>
<td>Turbopump Modeling for Engine Cycle Analysis</td>
<td>K. Pethe, DLR / Purdue University, U. S. A.</td>
<td></td>
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<tr>
<td>Untersuchung fortschrittlicher Hybrid-Treibstoffe für Höhenforschungsraketen</td>
<td>C. Schmierer, DLR / Universität Stuttgart</td>
<td></td>
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<tr>
<td>Numerische Untersuchung von Strömungsdetails in einer planaren Expansion-Deflection Düse</td>
<td>G. Stich, DLR / Universität Stuttgart</td>
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<tr>
<td>Untersuchung des Einflusses unterschiedlicher Rauheiten innerhalb eines Kanalquerschnitts von Kühlkanälen auf den Wärmeübergang innerhalb von Raketenschubkammern</td>
<td>A. Pfeifle, DLR / Universität Stuttgart</td>
<td></td>
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<tr>
<td>Additive Fertigungstechnologien für die Herstellung von Prototypen und funktionalen Raumfahrtelementen von morgen</td>
<td>S. Beyer, Airbus DS</td>
<td></td>
</tr>
<tr>
<td>Simulation of the commercial launcher market with modified Lotka-Volterra equations</td>
<td>F. Schubert, DLR / Hochschule Aachen</td>
<td></td>
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<tr>
<td>Progress in CFD Modelling of LOX/CH₄ Nozzle Flow Using DLR’s Flow Solver TAU</td>
<td>D. Schneider, DLR Lampoldshausan</td>
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<tr>
<td>Numerical simulation of water hammer with EcosimPro/ESPPSS</td>
<td>N. Cattaneo, DLR / Politecnico Di Milano</td>
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<tr>
<td>Heat Transfer analysis in a research rocket combustor BKD</td>
<td></td>
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<td>Development of an optical accessible combustion chamber for gelled propellants</td>
<td>P. Dern, DLR / RWTH Aachen</td>
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<tr>
<td>Parameterized Rocket Engine CAD Model for Visualization of Cycle Analysis Results</td>
<td>M. Bambauer, DLR / TU München</td>
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<tr>
<td>Acoustic Pressure Mode Reconstruction and Simulation in a Rectangular Rocket Combustion Chamber</td>
<td>F. Wöske, DLR / RWTH Aachen</td>
<td></td>
</tr>
<tr>
<td>Auslegung und mechanische Konstruktion eines multifunktionalen SCRamjet-Versuchskanals mit Transpirationskühlsystem</td>
<td>N. Gaiser, DLR / Universität Stuttgart</td>
<td></td>
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<tr>
<td>Analyse elektrischer Antriebssysteme als Ersatz für konventionelle Oberstufen</td>
<td>F. Schubert, DLR / Hochschule Aachen</td>
<td></td>
</tr>
<tr>
<td>Modifikation einer Versuchsbrennkammer zur Untersuchung der Wechselwirkung zwischen akustischen Anregungen und der Einspritzung</td>
<td>M. Geiger, DLR / Universität Stuttgart</td>
<td></td>
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<tr>
<td>Water Hammer Testing and Simulation for Spacecraft Applications</td>
<td>L. Zimmermann, ESA / Universität Stuttgart</td>
<td></td>
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<tr>
<td>Construction and Finite Element Analysis of SLM-TMF Panels</td>
<td>B. Jayaganesan, DLR / Nanyang Technical University</td>
<td></td>
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<tr>
<td>Experimental investigations into combustion instabilities in oxygen-rich staged rocket engines</td>
<td>S. Hester, Purdue University, U.S.A.</td>
<td></td>
</tr>
<tr>
<td>Experimentelle Charakterisierung von Ventilkomponenten zur Design-Optimierung eines Entlastungsventils</td>
<td>J. Zeifang, Airbus DS / Universität Stuttgart</td>
<td></td>
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<tr>
<td>Stufungs optimierung für ein Trägersystem mit LOX/Methan Antrieb</td>
<td>O. Kreis, DLR / Universität Stuttgart</td>
<td></td>
</tr>
<tr>
<td>Univ. Austin / JAXA Kakuda: Zwei kurze Austauschberichte</td>
<td>C. Génin, D. Schneider, DLR Lampoldshausan</td>
<td></td>
</tr>
</tbody>
</table>
Relativistische Jets
C. Fromm, DLR Lampoldshausen

Untersuchung von kleinen Trägerraketen für institutionelle Nutzlasten
S. Koss, DLR / RWTH Aachen

2015

Temperature and stress dependency of the permeability of C/C and OXIPOL flow probes
E. Sghaier, DLR / Supméca, Paris

Betrachtung der Anforderungen an Turbomaschinen in offenen Expanderzyklen
C. Groll, DLR / RWTH Aachen / TU Delft

Raketentreibstoff Wasserstoffperoxid (H2O2) – Eigenschaften, Leistungskennwerte, Handhabung
Prof. W. Koschel, DLR Lampoldshausen

Experimentelle Untersuchungen zu Skalierungsgesetzen und akustischen Eigenschaften von TOP-Düsenkonfigurationen
G. Mack, TU München / University of Texas

Simulation und Verifizierung eines instationären Modells des P8 Prüfstands
S. Erhard, DLR / Universität Stuttgart

Analyse optischer Aufnahmen einer experimentellen Raketenbrennkammer mit kryogener LOX/H2 Verbrennung
F. Pfähler, DLR / Universität Stuttgart

Lowthrust transfer optimization
C. Holst, DLR / Hochschule Aachen

Numerische Analyse der Kühlkanalströmung in einer wassergekühlten Brennkammer für Green Propellants
B. Hochheimer, DLR / Universität Stuttgart

Analyse niederfrequenter Verbrennungsinstabilitäten einer Nitromethan-Gel-Raketenbrennkammer
M. Wilhelm, DLR / Universität Stuttgart

Analyse dynamischer Effekte der Treibstoffeinspritzung durch Koaxialinjektoren in einer Forschungsraketenbrennkammer
J. Glowienka, DLR / Universität Stuttgart

Modal Decomposition of Supersonic Nozzle Flow
R. Larusson, Chalmers University, Sweden

The University of Toronto Aerospace Team: Or, how to design aircraft, rockets, and satellites as a student
J. Wang, DLR / Toronto University, Canada

Auslegung und Test einer CFK-Brennkammer für Hybridraketentriebwerke
S. Buchf elner, Airbus DS / Universität Stuttgart

Entwicklung eines GOX/GH2 Triebwerks
K. Manassis, Airbus DS / Universität Stuttgart

Untersuchung der Flammendynamik in einer Forschungsraketenbrennkammer mit akustischer Anregung
J. Martin, DLR / Universität Stuttgart

Combustion modelling at Stanford University
M. Ihme, Stanford University, U. S.A.

Data analysis of water hammer experimental data
J. Batut, DLR / Ecole des Mines d’Albi, France

Modal Decomposition of Fluid Flows and Aeroacoustics
N. Andersson, Chalmers University, Sweden

The influence of luni-solar perturbations on all-electric satellite transfers
C. Holst, DLR / Hochschule Aachen

The influence of luni-solar perturbations on all-electric satellite transfers
E. Mayer, DLR / Universität Erlangen-Nürnberg

Bewertungen verschiedener Trägerraketen für kommerzielle Kleinsatelliten
A. Strouvelle, DLR / RWTH Aachen

Quadrature-based lattice Boltzmann models for microfluidics and multiphase flows
V. E. Ambrus, V. Sofonea, Center for Fundamental and Advanced Technical Research, Romanian Academy
Teaching Activities

Since 2011 a group of DLR engineers gives lectures and practical exercises in our annual DLR_Summer_School as well as in the CVA Summer School.

**Technische Thermodynamik**, Duale Hochschule Mosbach, 2011-2016
Ciezki, H.,

**Treibstoffe**, Universität Stuttgart, 2014-2016
Ciezki, H.,

**Chemische Raumfahrtantriebe I**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2011-2016
Ciezki, H.,

**Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. M. Oschwald, RWTH Aachen, 2011-2012
Ciezki, H.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2015-2016
Deeken, J.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2013
Génin, C.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2015-2016
Gernoth, A.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2011-2016
Greuel, D.,

**Maschinendynamik**, Duale Hochschule Mosbach, 2011-2016
Haberzettl, A.,

**Chemische Raumfahrtantriebe**, Universität Stuttgart, 2011
Haidn, O.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2012-2016
Hardi, J.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2014-2016
Herbertz, A.,

**Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. M. Oschwald, RWTH Aachen, 2013-2016
Herbertz, A.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2011-2015
Kitsche, W.,

**Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. M. Oschwald, RWTH Aachen, 2011-2016
Kitsche, W.,

**Strömungsmaschinen**, Duale Hochschule Mosbach, 2011-2016
Kitsche, W.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2015
Kobald, M.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2012-2016
Koschel, W.,

**Ariane 5 Launcher Family, Space Transportation Systems**, Universität di Roma La Sapienza, 2011-2016
Koschel, W.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2013-2016
Kraft, V.,

**Chemische Raumfahrtantriebe**, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2011-2016
Manfletti, C.,
Raumfahrtantriebe, Beitrag zu Vorlesung Prof. M. Oschwald, RWTH Aachen, 2011-2016
Manfletti, C.,

Mathematik I-III, Duale Hochschule Mosbach, 2011-2016
Neumann, H.,

Chemische Raumfahrtantriebe, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2011-2013
Oschwald, M.,

Chemische Raumfahrtantriebe, RWTH Aachen, 2011-2016
Oschwald, M.,

Spacecraft System Design, Universität Würzburg, 2011-2016
Oschwald, M.,

Chemische Raumfahrtantriebe, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2012-2016
Riccius, J.,

Raumfahrtantriebe, Beitrag zu Vorlesung Prof. M. Oschwald, RWTH Aachen, 2011-2016
Riccius, J.,

Physik (Praktika), Hochschule Heilbronn, 2011-2016
Ritter, T.,

Chemische Raumfahrtantriebe, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2013-2016
Schäfer, K.,

Raumfahrtantriebe, Beitrag zu Vorlesung Prof. M. Oschwald, RWTH Aachen, 2011-2016
Schäfer, K.,

Festigkeitslehre I-III, Duale Hochschule Mosbach, 2011-2016
Schäfer, K.,

Chemische Raumfahrtantriebe I, Chemische Raumfahrtantriebe, ausgewählte Kapitel, Vorlesung,

Universität Stuttgart, 2011-2016
Schlechtriem, S.,

Technische Mechanik, Duale Hochschule Mosbach, 2012-2016
Schmidt, V.,

Festigkeitslehre und Statik, Duale Hochschule Mosbach, 2011-2012
Seeck, F.,

Konstruktionstechnik, Duale Hochschule Mosbach, 2011-2012
Seeck, F.,

Grundlagen Technische Mechanik, Duale Hochschule Mosbach, 2013-2016
Seeck, F.,

Mathematik I-III, Duale Hochschule Mosbach, 2011-2016
Sender, J.,

Chemische Raumfahrtantriebe, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2011-2016
Stark, R.,

Raumfahrtantriebe, Beitrag zu Vorlesung Prof. M. Oschwald, RWTH Aachen, 2011-2016
Stark, R.,

Regelungstechnik, Duale Hochschule Mosbach, 2011-2016
Stuchlik, W.,

Elektrotechnik, Duale Hochschule Mosbach, 2011-2016
Stuchlik, W.,

Messtechnik, Duale Hochschule Mosbach, 2011-2013
Stuchlik, W.,

Raumfahrtantriebe, Beitrag zu Vorlesung Prof. Oschwald, RWTH Aachen, 2011-2016
Suslov, D.,

Chemische Raumfahrtantriebe, Beitrag zu Vorlesung Prof. S. Schlechtriem, Universität Stuttgart, 2013-2015
Graduations

Diploma and Master

2011


Strauss, F. (2011) Numerische Untersuchung des heißgaskühlten Wandwärmeübergangs in konvektiv gekühlten Düsenverweiterungen von Flüssigkeitsabblassraketen, Universität Karlsruhe

Werling, L. (2011) Numerische Untersuchung des heißgaskühlten Wandwärmeübergangs in konvektiv gekühlten Düsenverweiterungen von Flüssigkeitsabblassraketen, Universität Karlsruhe


2012


Dilucca, P. (2012) Comparison of like-on-like doublet and triplet impinging jet injectors, Politecnico Milano, Italy


Carissimi, J. (2012) Investigation of the combustion process in hybrid rocket engines with energetic additives with a water-cooled sampling probe system, Politecnico Milano, Italy

Padoan, L. (2012) Dynamic behavior of a cryogenic system in a rocket propulsion system, Politecnico Milano, Italy


Wurdak, M. (2012) Auslegung eines Einspritzkopfes und Untersuchungen der Treibstoffaufbereitung von fortschrittlichen Treibstoffen (Green Propellants) als
Ersatz von Hydrazin für Anwendungen im Satellitenbereich, Hochschule Heilbronn

2013


Schneider, D. (2013) Numerische Untersuchung zur Optimierung von neuartigen höhenadaptiven Dual-Bell-Düsenerweiterungen mittels RANS-Simulation, RWTH Aachen


Costa, G. (2013) Student hybrid thruster testing and research, Politecnico Milano

Di Betta, S. (2013) Investigation of the combustion process of liquefying hybrid fuels with energetic additives, Politecnico Milano


2014


Teichmann, L. (2014) Charakterisierung und Design-Optimierung eines Formgedächtnis-Ventils Characterisation and design optimization of a shape memory alloy valve, Universität Stuttgart

Andersen, T. (2014) Auslegung von Blockheizkraftwerken (BHKW) für das DLR Institut für Raumfahrtantriebe und Wirtschaftlichkeitsbetrachtung
einer Rückverstromung von regenerativ erzeugtem Wasserstoff in Brennstoffzelle und BHKW, RWTH Aachen

Arboleda, J. C. (2014) CFD Modelling of Mixing in Shear Coaxial Jets under Supercritical Conditions, Hochschule Esslingen


Losco, P. L. (2014) Analysis of the first tangential mode in a cylindrical rocket engine combustion chamber equipped with an absorber, University of Pisa


Taules, L. (2014) Development of a water-based propulsion system for satellite applications, RWTH Aachen

Verri, I. (2014) Liquid Film Instability Analysis in a Hybrid Rocket Engine, Politecnico Milano


2015


Hauk, A. (2016) Experimentelle Untersuchung der Druckverluste von Injektorelementen- und Flammenrückschlagsicherungen für ein (N2O/C2H4) Premixed Green Propellant Triebwerk Experimental investigation of the pressure drop occurring in injector- and flashback-arrestor elements used for a N2O/C2H4 green propellant combustion demonstrator, Universität Stuttgart


Küpper, P. (2016) Numerische Untersuchung des Transitionsverhaltens starr ovalisierter Dual-Bell-Düsen, RWTH Aachen

Lauck, F. (2016) Experimentelle Untersuchung von Detonations- und Flammensperren für einen vorgemischten, grünen Raketentreibstoff aus Lachgas (N2O) und Ethen (C2H4) Experimental investigation of detonation and flame arrestors used for a premixed, green propellant consisting of nitrous oxide (N2O) and ethylene (C2H4), Universität Stuttgart

Müller, S. (2016) Auslegung, Konstruktion und Heißgastests von Injektoren zur Anwendung in einem Demonstratortriebwerk für einen Green Propellant aus Lachgas (N2O) und Ethen (C2H4) Design, Construction and Testing of Injectors used in a demonstrator unit for a Nitrous Oxide (N2O)/Ethene (C2H4) Green Propellant, Universität Stuttgart

Bachelor

2012


2013


Basov, L. (2013) Entwicklung eines Hybridtriebwerks für eine Höhenforschungsrakete, Universität Stuttgart


Kostyrkin, K. (2013) 3D-CFD-Ubersuchung einer Vorrichtung zur Reduktion von Seitenlasten in Rakendüsen, RWTH Aachen

der mobilen P8 Höhenanlage an den Prüfstand P8, Hochschule Bremen


2014


2015


2016


Witte, J. (2016) Inbetriebnahme und Modifikation der Prüfstandsmeßtechnik für eine transpirativ gekühlte
Scramjetmodellbrennkammer. Bachelorarbeit. DLR-Interner Bericht. DLR-IB-RA-LA-2016-252, 58 S.

PhD Theses

2011

2012


2013
Gernoth, A. (2013) Untersuchung der Turbulenzmodellierung von rauen Rechteckkanalströmungen mit Berücksichtigung der Oberflächenverformung im Hinblick auf die Anwendung in Raketenmotoren, Universität Stuttgart


2014


2015

Schaller, U. (2015) Synthese und Charakterisierung von energetischen ionischen Liquiden auf Basis 4-Amino-1,2,4-triazol, Universität Stuttgart

2016
Webster, S. (2016) Analysis of Pressure Dynamics, Forced Excitation and Damping in a High Pressure LOX/H₂ Combustor. RWTH Aachen

Awards
Frank, A., TOP 25 – die einflussreichsten Ingenieurinnen Deutschlands, Deutscher Ingenieurinnen Bund, 2011


Hardi, J., University Doctoral Research Medal, University of Adelaide, Australien, 2013


Memberships, Committees, Reviewers
Börner, M., LIC’17, 5th Laser Ignition Conference, Bucharest 2017, Steering Committee

Ciezki, H., Associate Editor of the International Journal of Energetic Materials and Chemical Propulsion

Ciezki, H., Member of the editorial advisory board of the Journal Propellants, Explosives, Pyrotechnics (PEP)


Ciezki, H., Committee activities: Member of: TC Solid Propulsion of the AIAA. Educational Subcommittee of the AIAA TC Solid Propulsion. Defense technology advisory committee of Fraunhofer Institute of Chemical Technology. Defense technology working group of BAAINBw „Propulsion Systems“. DGLR technical committees R1.3 „Rocket propulsion systems“, R1.2 „Space transportation systems“. NATO AVT Technical Teams. Head of special technical group „Advanced propulsion systems and components“ of DGLR technical committee R1.3.

Ciezki, H., Memberships: American Institute of Aeronautics and Astronautics (AIAA), Senior Member. German Section of the Combustion Institute. Association of German Engineers (VDI). German Aerospace Society (DGLR). ILASS Europe.


Hardi, J., Member Scientific Committee on the French / German Cooperation: Rocket Engine Stability Initiative (REST).

Hardi J., Reviewer: Advances in Mechanical Engineering

Kobald, M., Member of the AIAA Hybrid Rockets Technical Committee.


Koschel, W.: Member of the Ariane 5 ME review: Ariane 5 ME Verification Key Point at ESA, Paris, (Dec. 2014)

Koschel, W.: Member and co-chairman of the Ariane 6 review: Ariane 6 Verification Key Point at ESA, Paris, (Oct. 2015)

Koschel, W.: Member of the Ariane 6 review: Ariane 6 Maturity Gate 5 (MG 5) at ASL, Les Mureaux, (April/May 2016)


Oschwald, M., Reviewer for Funding Institutions: ANR (French National Research Agency), NSRC (Natural Sciences and Engineering Research Council of Canada), PRACE (Partnership for Advanced Computing in Europe)
Oschwald, M., Editor: CEAS Space Journal (Field Editor Combustion)

Oschwald, M., Memberships: Scientific Committee of the French/German Cooperation on High Frequency Instabilities REST, Scientific Coordination Committee Research of the French/German Cooperation on High Pressure Combustion, DLR/ONERA Partnership MOTAR (Measurement and Observation Techniques for Aerospace Research), ESA FLPP (Future Launcher Preparatory Program) Expert Team, American Institute of Aeronautics and Astronautics (AIAA), Deutsche Gesellschaft für Luft- und Raumfahrt, Deutsche Physikalische Gesellschaft, EUCASS, Technical Committee of the EUCASS Conference


Riccius, J., Member of American Institute of Aeronautics and Astronautics (AIAA). AIAA Liquid Propulsion Technical Committee. ISP-1 Steering Committee member. DLR Network of the foreign relations representatives

Schäfer, K., Board Member LR BW - Forum Luft- und Raumfahrt Baden-Württemberg e.V. Member TTZ Forum, Lampoldshausen.

Schäfer, K., Vice President CVA (Communauté des Villes Ariane), 2016.

Schäfer, K., DLR Representative Forum Ariane, Lampoldshausen.

Schlechtriem, S., Member of TC Space Propulsion Conference. Member of P8 Scientific Coordination Committee Research.

Schlechtriem, S., Reviewer: CEAS Space Journal.

Schlechtriem, S., Kurator, ICT Pfinztal.

Sender, J., Member of P8 Scientific Coordination Committee Research. IT Manager, RA (Vorsitzender)


Stark, R., Expert: Sächsisches Staatsministerium für Wissenschaft und Kunst

Stark, R., Technical Assistance: ESA

Stark, R., Member of Flight Physics Technical Committee: EUCASS. ESA FLPP (Future Launcher Preparatory Program) Expert Team


Suslov, D., Member of P8 Scientific Coordination Committee Research


Guest Scientists / Leaves
Instituto e Aeronáutica e Espaço (IAE), Brazil (Senior Scientists)

Bartholomeu do Nascimento, L., July 2016
Reis Dreyer de Souza, B., June-July 2016, S Dybal, A., July 2016
Vianna de Ferreira Bandeira, B., June-July 2016
Costa, J.M., June-July 2016
Mendes Bernardes, J.A., July 2016
Barbosa de Araujo, T., June-July 2016
Neves de Almeida Prado, A., June 2016
Miquelof dos Santos, E., June 2016
Stanice Correa W., June-July 2016

Andersson, J.N., Universität Göteborg, September 2015, Professor

Lárusson, R., Chalmers University of Technology, Sweden, September-October 2015, Graduate

Ambrus, V.E., West University of Timisoara, Romania, November 2015, Scientist

Sofonea, V.M.C., Center for Fundamental and Advanced Technical Research, Roman Academy, Timisoara, Romania, November 2015, Scientist

Cuenot, B., CERFACS, France, June 2016, PhD

Fdida, N., ONERA, F, May-June 2014, Scientist
Selle, L., Institut de Mécanique des Fluides, France, September 2013, Guest Scientist

JAXA, Japan (Guest Scientists)

Masuoka T., March 2016-February 2017

Kawashima, H., February 2014-January 2015

Kurosu, A., November 2012-October 2013

Leaves

ESA, Paris

Greuel, D., April 2012-January 2014, Scientist

Schoroth, W., September 2014-December 2017, Scientist

Lutz, P., July 2008-December 2016, Scientist

Schmierer, C., ESA/ESTEC, Noordwijk, NL, February-August 2016, Scientist

Brüssow, T., JAXA, Japan, January-February 2013, Scientist

Hardi, J., Purdue University, U.S.A., February-October 2013, Scientist

Génin, C., CNES, Paris, July-December 2016, Senior Scientist

Events and Campaigns

2011

[1] BOGY week, 01 – 04 March

[2] BOGY week, 14 – 18 March

[3] Teacher Seminar, Neckarsulm, 13 April


[6] Scientific Summer, Mainz, 04 – 06 June

[7] Corner Stone Ceremony, DLR-Forum, 10 June

[8] Water rocket workshop, 14 – 16 June

[9] Solid fuel rocket workshop, 20 – 22 June


[14] Fascinating Science, Heilbronn, 08 September

[15] DLR_Summer_School, 12 – 23 September

[16] Teacher Seminar, University Hohenheim, 20 September

[17] Teacher Seminar, Möckmühl, 28 September

[18] IAC, Cape Town, 03 – 07 October

[19] Solid fuel rocket workshop, MiNe MINT, 02 – 04 November


2012

[21] Green Academy, Bildungscampus, 23 January

[22] Green Academy, Bildungscampus, 25 January

[23] Solid fuel rocket workshop, 01 – 03 February

[24] BOGY week, 19 – 23 March

[25] Intercultural Workshop Robotik and Rockets, 14 – 22 April

[26] ISS Call, Museum Speyer, 24 April

[27] Girls’ Day, 26 April

[28] Energy Workshop, 29 – 31 May

[29] Week of the Environment – Schloss Bellevue, Berlin,

[30] DLR presents SOWARLA, 05 – 06 June

[31] Scientific Holidays CVA, 02 July
<table>
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<tr>
<th>Year</th>
<th>Event</th>
<th>Date</th>
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<tbody>
<tr>
<td>2011</td>
<td>Scientific Holidays CVA</td>
<td>05 July</td>
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<tr>
<td>2011</td>
<td>European Space Technology Transfer Forum, Brüssel</td>
<td>09 – 10 July</td>
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<tr>
<td>2011</td>
<td>Children Holiday Program, Hardthausen</td>
<td>02 August</td>
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<td>2011</td>
<td>Children Holiday Program, Widdern</td>
<td>02 August</td>
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<td>2011</td>
<td>60 years Baden-Württemberg</td>
<td>10 September</td>
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<td>2011</td>
<td>ILA, Berlin</td>
<td>11 – 16 September</td>
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<tr>
<td>2011</td>
<td>DLR_Summer_School</td>
<td>17 – 28 September</td>
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<td>2011</td>
<td>Open Day, Realschule Pfedelbach</td>
<td>30 September</td>
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<td>2011</td>
<td>KLETT-MINT</td>
<td>04 October</td>
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<td>2011</td>
<td>Mission Zukunft, Stuttgart</td>
<td>05 October</td>
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<td>2011</td>
<td>IAC, Neapel</td>
<td>01 – 05 October</td>
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<td>2011</td>
<td>Stuttgarter Messe Herbst</td>
<td>16 – 25 November</td>
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<td>2011</td>
<td>Helmholtz Day</td>
<td>20 November</td>
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<td>2012</td>
<td>New Year’s Reception</td>
<td>19 January</td>
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<td>2012</td>
<td>Schau Schlau, Sindelfingen</td>
<td>01 February</td>
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<td>2012</td>
<td>Workshop with Airbus laureates</td>
<td>03 – 04 February</td>
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<td>2012</td>
<td>Propulsion Day</td>
<td>19 February</td>
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<td>2012</td>
<td>2. Industrial Day</td>
<td>26 February</td>
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<td>2012</td>
<td>BOGY week</td>
<td>24 – 28 February</td>
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<td>2012</td>
<td>BOGY week</td>
<td>10 – 14 March</td>
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<tr>
<td>2012</td>
<td>BOGY week</td>
<td>17 – 21 March</td>
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<td>2012</td>
<td>Girls’ Day</td>
<td>27 March</td>
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<td>2012</td>
<td>Ideas 2020, Stuttgart</td>
<td>08 April</td>
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<td>2012</td>
<td>Yuri Night, Stuttgart</td>
<td>12 April</td>
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<td>2012</td>
<td>Space Propulsion Conference, Cologne</td>
<td>19 – 22 May</td>
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<td>2012</td>
<td>Space Night Alexander Gerst</td>
<td>28 May</td>
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<td>2012</td>
<td>Solid fuel rocket workshop</td>
<td>23 – 27 June</td>
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<td>2012</td>
<td>2. Wasserstofftag</td>
<td>10 July</td>
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<tr>
<td>2012</td>
<td>Open Day DLR Stuttgart</td>
<td>12 July</td>
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<td>2012</td>
<td>Kinder- und Heimatfest</td>
<td>19 July</td>
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<td>2013</td>
<td>Opening STERN Testbench in Lampoldshausen</td>
<td>10 June</td>
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<tr>
<td>2013</td>
<td>Opening DLR-Forum, Lampoldshausen</td>
<td>28 June</td>
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<tr>
<td>2013</td>
<td>Open Day in Lampoldshausen</td>
<td>30 June</td>
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<tr>
<td>2013</td>
<td>CVA Summer School</td>
<td>22 – 31 July</td>
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<td>No.</td>
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<tr>
<td>1</td>
<td>DLR_Summer_School, 28 July – 08 August</td>
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<td>2</td>
<td>Children Holiday Program, Hardthausen, 14 August</td>
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<td>3</td>
<td>Children Holiday Program, Widdern, 14 August</td>
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<td>4</td>
<td>Science Academy, 08 September</td>
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<td>5</td>
<td>Aerospace Academy, Böblingen, 09 September</td>
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<td>6</td>
<td>Corner Stone Ceremony P5.2, 10 September</td>
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<td>7</td>
<td>IAC Toronto, 29 September – 03 October</td>
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<td>8</td>
<td>Teacher Seminar, F.- Hecker-Schule, 02 October</td>
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<td>9</td>
<td>IT-Sicherheitstag, Lampoldshausen, 08 October</td>
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<td>10</td>
<td>Mission Zukunft, Stuttgart, 10 October</td>
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<td>11</td>
<td>Teacher Seminar, Justinus-Kerner-Gymnasium, Weinsberg, 16 October</td>
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<td>12</td>
<td>Teacher Seminar, Gymnasium Weikersheim, 17 October</td>
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<td>13</td>
<td>Technikforum Göppingen, 30 October</td>
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<td>14</td>
<td>Wissensfabrik, 29 November</td>
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<td>15</td>
<td>2015</td>
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<td>16</td>
<td>Lebenshilfe Sinsheim, 21 January</td>
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<td>17</td>
<td>STERN Workshop, 27 – 30 January</td>
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<tr>
<td>18</td>
<td>Eduard-Mörike-Gymnasium, Neuenstadt, Student Exchange with France, 10 February</td>
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<td>19</td>
<td>BOGY week, 09 – 13 February</td>
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<td>20</td>
<td>5. Wirtschaftsforum, GIK, Neuenstadt, 12 March</td>
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<tr>
<td>21</td>
<td>CVA Intercultural Seminar, 23 – 27 March</td>
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<td>22</td>
<td>BOGY week 23 – 27 March</td>
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<td>23</td>
<td>Lycée Stoessel, Mulhouse, 15 April</td>
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<td>24</td>
<td>Visit Dr. Kaufmann, Bundestagsabgeordneter, 16 April</td>
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<td>Yuris Night, Stuttgart, 18 April</td>
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<td>102</td>
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<td>104</td>
<td>Visit Reinhold Würth, 29 April</td>
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<td>105</td>
<td>Welcome Alexander Gerst, Künzelsau, 09 May</td>
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<td>106</td>
<td>Solid fuel rocket workshop, 08 – 12 June</td>
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<td>107</td>
<td>Le Bourget Exhibition, Paris, 15 – 21 June</td>
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<td>108</td>
<td>Tag der kleinen Forscher, 23 June</td>
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<td>109</td>
<td>Teacher Seminar, Eduard-Mörike-Gymnasium, Neuenstadt, 26 June</td>
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<td>110</td>
<td>Kinder-und Heimatfest, Vaihingen, 11 July</td>
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<td>111</td>
<td>Visit Ministerialdirektor Rebstock, 15 July</td>
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<td>112</td>
<td>Children holiday program, Hardthausen, 12 August</td>
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<td>113</td>
<td>Children holiday program, Widdern, 12 August</td>
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<tr>
<td>114</td>
<td>Doktoranden Symposium, 02 – 04 September</td>
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<td>115</td>
<td>Aerospace Academy, Böblingen, 08 September</td>
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<tr>
<td>116</td>
<td>Workshop on aeronautical applications of fuel cells and hydrogen technologies, 15-16 September</td>
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<td>117</td>
<td>DLR_Summer_School, Lampoldshausen, 21 September – 02 October</td>
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<td>118</td>
<td>P5.2 Richtfest, 29 September</td>
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<td>119</td>
<td>2. IT-Sicherheitstag, 08 October</td>
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<td>120</td>
<td>Experimenta Heilbronn, Klett-MINT, Lehrerkongress, 21 October</td>
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<td>121</td>
<td>MissionX 2016, Lehrer Info Veranstaltung, 16 November</td>
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<td>122</td>
<td>Standordialog, 10 December</td>
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<td>123</td>
<td>German Trainee Programme, 18 December</td>
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</table>
2016

[124] New Year’s Reception, Hardthausen, 16 January

[125] Site tour Prof. Ehrenfreund, 19 January

[126] STERN workshop, 26 – 27 January

[127] MOU mit Hochschule Heilbronn, 02 February

[128] ALL.täglich, Raumfahrtausstellung im Haus der Wirtschaft, Stuttgart, 11 February


[130] Eduard-Mörke-Gymnasium, Neuenstadt, Student Exchange with France, 09 March

[131] Teacher seminar, 15 March

[132] BOGY week, 14 – 18 March

[133] BOGY week, 11 – 15 April

[134] CVA Council of Mayors, 21 April

[135] Visit Kosmonaut Padalka, 27 April


[137] Space Propulsion Conference Rome, 02 – 06 May

[138] Schüler Ingenieur Akademie, Heilbronn, 04 May

[139] Solid fuel rocket workshop, 30 May – 03 June

[140] ILA Berlin Exhibition, 01 – 04 June

[141] CVA Reception, Landesvertretung Baden-Württemberg, Berlin, 02 June

[142] Einweihung physikalisch-chemisches Labor M3, 08 June

[143] Tag der kleinen Forscher, 21 June

[144] 4. Wasserstofftag, 07 July

[145] Landesgartenschau Öhringen, School Lab, 16 July

[146] REVA Teachers Space Training (CVA), 18 July

[147] Children holiday program, Hardthausen, 09 August

[148] Children holiday program, Widdern, 09 August

[149] DLR_Summer_School, Lampoldshausen, 05 – 16 September

[150] Tag des offenen Forums, 17 September

[151] 1st Lampoldshausen Symposium on advanced rocket propellants research and development, 23 September

[152] 3. IT-Security Days, 28 – 29 September

[153] Mission Zukunft, Stuttgart, 04 October

[154] European Space Technology Transfer Forum, Brüssel, 17 – 18 October

[155] Kinderuni Weil der Stadt, 02 – 04 November

[156] Helmholtz Tag, 15 November