IAC-19,C4,9,1,x49899

TEST COMPLEX M11: RESEARCH ON FUTURE ORBITAL PROPULSION SYSTEMS AND SCRAMJET ENGINES

Wilhelm, M.*, Werling, L., Strauss, F., Lauck, F., Kirchberger, C., Ciezki, H., Schlechtriem, S.

German Aerospace Center (DLR), Institute of Space Propulsion, Hardthausen, Germany
* Corresponding Author: Marius.wilhelm@dlr.de

Basic research activities and thrust chamber oriented technology development for rocket and air-breathing (Ram-/SCRamjet) propulsion systems are conducted at Test Complex M11. History of M11 dates back to the year 1966, when the first building was constructed. Since its existence, lots of scientific results could be elaborated in the multifarious working areas and have been published in a large number of publications in journals and on conferences. Today's research and development activities are focused on combustion, ignition, cooling and chamber processes of advanced green propellants for rockets, satellites and orbital propulsion systems. Furthermore material testing as well as propellant synthesis and analysis are performed. This publication gives a short overview of the history of the test complex and delivers an inside into current research activities.

1. HISTORICAL ACTIVITIES [1]

Test Complex M11 at DLR site Lampoldshausen was built in the 60s of the 20th century. A laboratory building named M11 with two test cells, a small office and laboratory wing was constructed in 1966. Fig. 1 shows an image during the construction. Recessed on the left side of the image the two test cells can be seen. The office and laboratory wing was enlarged in 1979 and 1980 as well as the test cell area. While the existing laboratory rooms were used for work in the area of analytical and preparative chemistry, the new laboratories were dedicated to advanced physical measuring techniques and work in the area of physical chemistry. In the following years several laser-based techniques, like CARS, LIF, LDA, and PIV were prepared, tested, enhanced and used with regard to the applicability in rocket and ramjet model combustors and experimental setups.

The physical-chemical laboratory and a large part of the offices moved to the M3 building in 1992. This was necessary because a larger safety radius was needed to conduct the test runs for the development of the Vulcain engine for Ariane 5 at the new test bench P5. The close collaboration between the physical-chemical laboratory and the test complex was and still is indispensable despite the spatial distance.

On June 10th 2013 the student test field M11.5 was inaugurated. Since then it is available for DLR research activities as well as for student groups of German universities, for example during the STERN program (STudentenRaketeN). Fig. 2 shows the current view of the M11 with the student test field M11.5 on the left side.

Fig. 1. Test Complex M11 during construction

2. PRESENT ACTIVITIES

2.1. Facilities

Test Complex M11 consists of 4 test facilities, M11.1 to M11.4, in two test cells. Furthermore, a research and student test field, called M11.5, completes the test repertoire.

Each test position is equipped with up-to-date remote control and measuring systems to enable complex investigations on flow, ignition and combustion processes. 200 bar gas supply systems for GH_2, GO_2, GN_2 and pressurized air offer a high flexibility for different test campaigns.

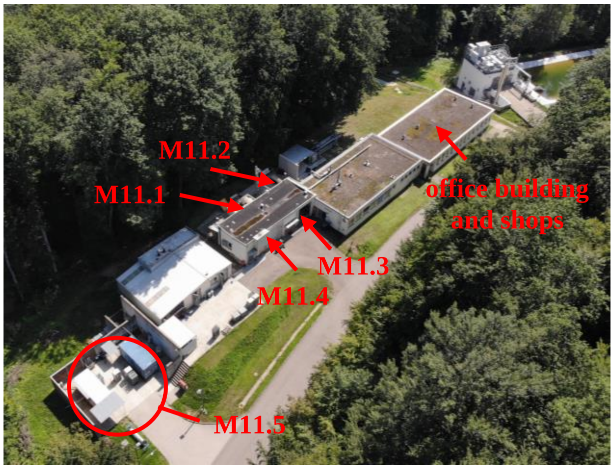

Fig. 2. Test Complex M11 today

1.1.1 M11.1

Test position M11.1 is equipped with an air vitiator for simulation of Ram-/SCRamjet combustor entrance conditions. The air vitiator in its current version is able to deliver up to 5 kg/s hot air at up to 1500 K total temperature and 25 bar of total pressure. SCRamjet combustor processes with a transpiratively cooled wall structure are currently investigated.

1.1.2 M11.2

At M11.2 high altitude tests for orbital propulsion systems are conducted inside a vacuum chamber. Investigation of injection processes of advanced propellants for satellite propulsion systems and hazard-free simulation fluids are conducted. Furthermore the combustion and ignition behavior or thermal balance can be investigated. Additionally thruster pulse mode firings and performance evaluations can be carried out. For evacuation purposes mechanical vacuum pumps and a two-staged nitrogen-cold-gas ejector-diffusor system is used.

1.1.3 M11.3

The combustion behavior of fuel/oxidizer combinations for hybrid rockets is under investigation at M11.3. Various solid propellants are burned with gaseous oxygen. In 2010 work on hybrid rockets was restarted at Lampoldshausen at this test position. For the investigations planar step combustor is used here in a modified version [2]. The optical access via large windows at both sides of the chamber offers the use of high-speed cameras for the observation of the combustion and ignition processes. A further small model combustor for cylindrical fuel grains allows investigations of combustor processes under boundary conditions closer to reality

1.1.4 M11.4

Combustor process investigations with gel propellants are conducted at M11.4. Two propellant feeding devices allow mono- as well as bipropellant combustor tests. At this test position investigations on reduction of combustor sizes, influence of additives, and ignition and combustion properties are conducted.

1.1.5 M11.5

The research and student test field M11.5 was inaugurated in 2013 and hosts two test containers for small and medium size rocket engines and model combustors. This test field is available for student groups especially for the ones which are funded by the DLR Space Management within the STERN program, see e.g. [3].

1.1.6 Physical-Chemical Laboratory

At the physical-chemical laboratory advanced propellants are developed and pre-qualified. Furthermore, the laboratory offers support in synthesis and chemical analysis for other departments of the institute and external customers. The laboratory complex consists of four laboratory rooms in the M3 building and a remote controlled research-scale propellant production facility in G49, which is located next to M11. Beside state-of-the-art analytical apparatuses and a wide-ranging know-how in handling of energetic materials, the available infrastructure allows the handling of propellants which are subject to the German explosive law. The diagnostic possibilities cover wet chemistry and instrumental analytics for the investigation of gaseous, liquid, gelled and solid probes by spectroscopic and chromatographic diagnostic tools up to the determination of physical and chemical parameters of low and high viscous fluids. The spectroscopic methods allow structure determination, proof of identity, and quantitative determination of gaseous, liquid and solid substances as well as trace analysis of a large number of elements and molecules. The infrastructure of the two fuel and oxidizer laboratory rooms allows the safe handling of storable propellants like hydrazine, dinitrogen textroxide (NTO, N_2O_4), hydrogen peroxide, etc. The infrastructure is also suitable for investigations on material compatibilities [4], ignition behavior of hypergolic propellant combinations and determination of material properties

2.2. Current Research Topics

2.2.1. Nitrous Oxide-Fuel Mixtures

2.2.1.1. *Motivation and State-of-the-art*

Currently hydrazine (N_2H_4) is the commonly used monopropellant to power satellites, planetary probes or landers. Advantages of hydrazine are its sufficient I_{sp} (up to 240 s), the long term storability, it can easily be decomposed via catalyst and an explosion of the propellant is very unlikely [5].

Additionally, hydrazine is used as a hypergolic fuel with the oxidizer dinitrogen tetroxide (N_2O_4). The hypergolicity of this bipropellant combination makes an ignition system redundant and is used e.g. in re-ignitable rocket stages [6].

Despite those advantages the use of hydrazine is challenging, caused by the high toxicity and carcinogenicity of the substance. Thus for fueling and testing of a propulsion systems high safety precautions are needed. Those precautions make handling and transportation of hydrazine a complex and costly process. As a consequence of the toxicity issues, hydrazine was added to the candidate list of substances of very high concern (SVHC) in the frame of EU's REACH (Europe's Registration Evaluation Authorization and Restriction of Chemicals) regulation [7]. Thus, the use of hydrazine could be restricted or even forbidden in the future what may have significant impact on the space industry.

Caused by the mentioned economic and political reasons several alternatives for hydrazine are currently under investigation.

A prospective, low cost and high performance alternative to hydrazine are mixtures of nitrous oxide (N_2O) and fuels, also known as nitrous oxide fuel blends. Here nitrous oxide and one or more fuels are stored pre-mixed as monopropellant in one tank. These mixtures offer a performance similar to bipropellants ($I_{sp} \geq 300$ s), while only one tank and one feeding system is needed. In addition to this simplified fluid system, self-pressurization of the propellant tank is possible due to the high vapor pressure of nitrous oxide. Furthermore the propellants are non-toxic and consist of very cheap constituents.

In contrast to those benefits, the two main challenges regarding N_2O/fuel propellants are the high combustion temperature and the danger of a flame flashback from the combustor into the propellant tank. To handle the high combustion temperatures, a future thruster needs an active cooling system. To avoid flame flashback, suitable flashback arresters for the propulsion system have to be designed, tested and qualified.

Nitrous oxide fuel blends were initially investigated and patented by Firestar engineering in the USA. Firestar developed a propellant consisting of N_2O, C_2H_2, C_2H_4, C_2H_6 and use CO_2 as a stabilizer [8]. They call their propellant mixture NOFBX (Nitrous Oxide Fuel Blend X) [9, 10]. A demonstration of the propellant and the corresponding thruster was scheduled for 2013 on board the ISS, but never took place [11].

In addition to the activities in the USA, at the Shanghai Institute of Space Propulsion in China an experimental 25 N engine propelled with NOFBX was tested. Here the NOFBX was used in liquid form and several seconds of steady state firing time were achieved. Furthermore the thruster was operated in pulse mode [12].

In Europe, ESA funded a study on nitrous oxide fuel blends. The study was conducted by TNO, NAMMO Westcott and Bradford Engineering in between 2015 and 2018; here a propellant mixture consisting of nitrous oxide and ethanol was investigated. The activity included a basic propellant formulation screening, investigations on the miscibility of the propellant components, a system study and several hot firings [13–15].

Furthermore the German Aerospace Center DLR investigates a propellant mixture consisting of N_2O and C_2H_4 or C_2H_6. The propellant is called "HyNOx" (hydrocarbons mixed with nitrous oxide) and is analyzed in thruster tests, flashback experiments and regarding its basic combustion mechanisms. The following chapters will give a short overview of DLRs activities on nitrous oxide/hydrocarbon mixtures.

2.2.1.2. DLR Activities Concerning Premixed N_2O/Hydrocarbon-Propellants

DLR investigates a nitrous oxide/fuel propellant within the framework of the interdisciplinary Future Fuels project [16]. The research activities started in a precursor project in 2014 and will run until 2021. An aim of the project is a successful test of a regeneratively cooled 22 N thruster under vacuum conditions at the M11.2 test bench in Lampoldshausen [17].

The Institute of Combustion Technology in Stuttgart and the Institute of Space Propulsion in Lampoldshausen are working closely together to study the properties of a N_2O/C_2H_4 and a N_2O/C_2H_6 premixed monopropellant. The mixture of N_2O and C_2H_4/C_2H_6 was chosen due to similar vapor pressures of the oxidizer and fuels, the possibility to liquefying the substances under ambient temperatures and elevated pressures and their good performance (I_{sp}). Mixtures of N_2O and C_2H_2 achieve an even higher I_{sp}, but a premixed propellant with C_2H_2 as fuel was considered to be to hazardous due to the possibility of self-decomposition of C_2H_2 [18]. The N_2O and C_2H_4/C_2H_6 premixed propellant was called "HyNOx" (hydrocarbons mixed with nitrous oxide). Table 1 gives some basic parameters of a N_2O/C_2H_4, respectively N_2O/C_2H_6 propellant mixture.

Property	**N_2O/C_2H_4**	**N_2O/C_2H_6**
I_{sp} [s] ($O/F, P_c, A_e/A_t$)	305 (6, 10 bar, 50)	301 (7, 10 bar, 50)
Density [kg/m^3] (0°C, 70 bar)	706	761
T_c [K]	3263	3129

Table 1. Properties of Hydrocarbon/Nitrous Oxide propellants

Within the Future Fuels project the following investigations are carried out:

- Analyze the basic combustion behavior of the premixed propellant. Derive ignition delay times and measure laminar flame speeds [19, 20] .
- Develop and reduce reaction mechanisms for N_2O/C_2H_4 and N_2O/C_2H_6 [21] for use in CFD.
- Analyze the theoretical and experimental quenching diameters for the propellant mixtures. Test and evaluated suitable flashback arresters.
- Investigate possible ignition methods for an experimental combustion chamber
- Assess the influencing factors on c*- or on the combustion efficiency, derive the characteristic chamber length L* and investigate the heat flux to the chamber walls
- Investigate if a regenerative cooling system for the combustion chamber is feasible. Design an experimental setup to test the cooling capabilities of the propellant.

In the following section some results of the above mentioned research areas are shown.

2.2.1.3. Research Activities: Evaluation of Flashback Arresters

To safely operate a thruster or combustion chamber with a premixed monopropellant, flame flashback from the combustion chamber to the feeding system must be avoided under all possible circumstances. Otherwise, in case of a flashback the flame might propagate into the tank and destroy the whole spacecraft.

Thus suitable flashback arresters for the thruster's feeding system need to be designed and tested. To investigate the flame propagation process, the flame propagation speeds and possible flashback arresters, a test setup was employed. The setup consists of two chambers, separated by porous materials or capillaries which serve as flashback arrester. Via two windows, high speed videos of the flame propagation and flashback process are recorded. Additionally temperature and pressure measurements are used to investigate, if the flame passed the flashback arrester or not [22, 23].

Different capillaries and porous materials were investigated regarding their ability to quench the flame. Furthermore the critical quenching diameters for various ignition pressure levels were derived experimentally and compared to theoretical predictions. The results of the basic flashback tests were used to design flashback arresters for the experimental rocket combustion chamber.

Fig. 3 shows a high speed image of the flame propagation inside the test chamber. The blue hydrocarbon flame front can be seen in the center of the picture, the mixture is ignited via spark plug and the flashback arrester is located in between the two chambers.

Fig. 3. High speed image of flame propagation inside the ignition and flashback test setup

In addition to the experiments, numerical simulations of the combustion process were conducted. Thus a better understanding of the combustion process could be gained. To simulate the flame inside the ignition test setup, the reaction mechanisms derived by the Institute of Combustion Technology [19, 20] were used.

2.2.1.4. Research Activities: Experimental Combustion Chamber

To analyze the ignition, injection and combustion behavior of the premixed HyNOx propellants, an experimental rocket combustion chamber was designed, built and successively improved. Fig. 4 shows the combustion chamber during a hot run.

The chamber was used to investigate if a H_2/O_2 torch igniter, a spark plug or a glow plug could be used as ignition source. Finally a spark plug was chosen as ignition method due to a very reliable and repeatable ignition.

In a further test series different flashback arresting elements were tested. As already suggested by the flashback experiments, porous materials confirmed their applicability as flashback arresters in the feeding lines of the combustion chamber.

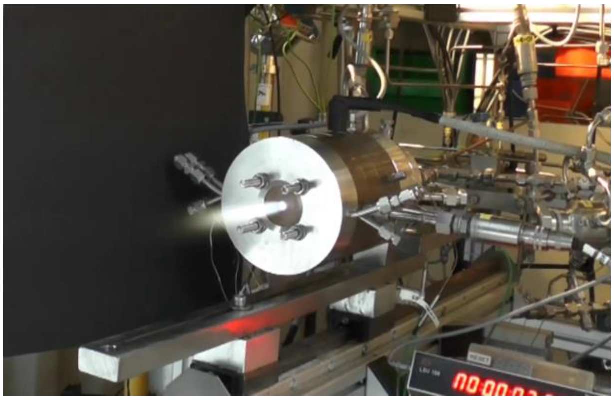

Fig.4. Hot run of the experimental combustion chamber

Additional test campaigns were conducted to investigate the influence of the characteristic chamber length L^*, the mixture ratio, the chamber pressure and the mass flow on the combustion efficiency η_{c*} [24–26]. Furthermore the heat loads on the combustion chamber walls were analyzed [26, 27].

Based on the results of the above mentioned test campaigns, a regeneratively cooled combustion chamber was designed and built. Combustion tests with the cooled chamber will take place at the end of 2019.

2.2.2. Hydrogen Peroxide

2.2.2.1. Motivation and State-of-the-art

Propellants based on hydrogen peroxide are a possible alternative to commonly used toxic propellants. Hydrogen peroxide (H_2O_2) is a chemical compound that is widely used in several industrial applications such as bleaching, disinfection or other chemical processes. High concentrations of hydrogen peroxide (more than 70 % diluted with water) can be decomposed into water vapor and gaseous oxygen by a suitable catalyst. The decomposition reaction is exothermic. Therefore, highly concentrated hydrogen peroxide can be used as monopropellant or oxidizer in a bipropellant system. Moreover, hydrogen peroxide is less toxic than common storable oxidizers such as dinitrogen tetroxide (NTO), mixtures of nitrogen oxides (MON), white or red fuming nitric acid.

2.2.2.2. Monopropellant Research and Development Activities

At the test facility M11.2 a 1 N hydrogen peroxide thruster was tested under high altitude conditions in collaboration with Ariane Group [28,29], see Fig. 5. Therefore a hydrogen peroxide compatible propellant supply system was set up. The test activities investigated the thruster's performance under different operating conditions. The tests were successful and first performance data of the thruster with hydrogen peroxide at a concentration around 98% were determined.

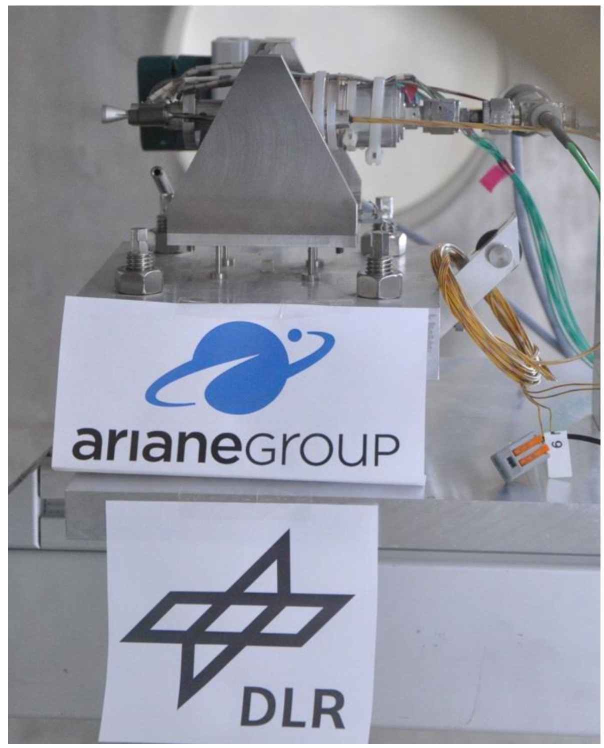

Fig. 5. Mounted 1 N hydrogen peroxide thruster

2.2.2.3. Hydrogen Peroxide Bipropellant Activities

Research activities focus on the development of liquid green hypergolic propellants based on hydrogen peroxide for orbital propulsion. The investigated alternative fuels are room temperature ionic liquids [30]. Due to the fact that ionic liquids are composed of large anions and cations, they have a negligible vapor pressure at ambient conditions. This offers a reduced risk during handling of those substances. Furthermore ionic liquids have a high density and their properties can be influenced or tuned by combining different anions and cations.

The development of hypergolic propellants is conducted in several steps. After the identification of possible fuels and purchase or synthesis of the candidate fuels, the reactivity between fuel and oxidizer is investigated in so called drop tests. Here, one component is dropped into the other component of the propellant. The process is recorded with a high speed camera. The ignition delay is determined between the first contact of fuel and oxidizer and the first appearance of a flame.

The development aims for fuels with ignition delay times in the order of 10 ms or below, which are beneficial for reliable and smooth ignition of a thruster. Fig. 6 shows a series of snapshots during a drop test with hydrogen peroxide and an ionic liquid with a dissolved catalytic additive [31]. In this particular drop test the ignition delay is 29.5 ms. In a further step, fuels with a short ignition delay time in drop tests are tested under more relevant conditions for a later application.

Therefore the hypergolic ignition test setup (HIT) was set into operation [32]. HIT consists of a bipropellant supply system and a modular optical accessible reaction chamber, which is shown in Fig. 7. First tests with a proven hypergolic fuel (Block 0; 78% methanol and 22% manganese acetate tetrahydrate) and hydrogen peroxide were conducted and ignition was achieved. Fig. 8 shows the ignition of the propellant during a test with a 2-on-1 impinging jet injector. HIT allows the use of different injectors and the variation of injection parameter by adjusting the supply pressure of the propellant. With HIT tests a suitable injector for reliable and fast hypergolic ignition will be developed. Based on these results, it is planned to develop a demonstrator unit for the investigation of the performance of the newly developed hypergolic fuels.

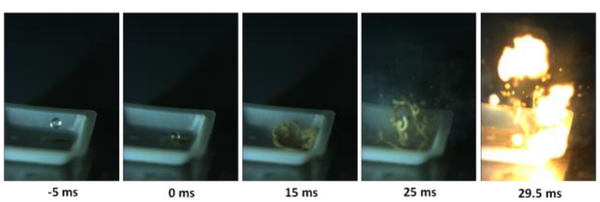

Fig. 6. Drop test of an ionic liquid with dissolved catalytic additive

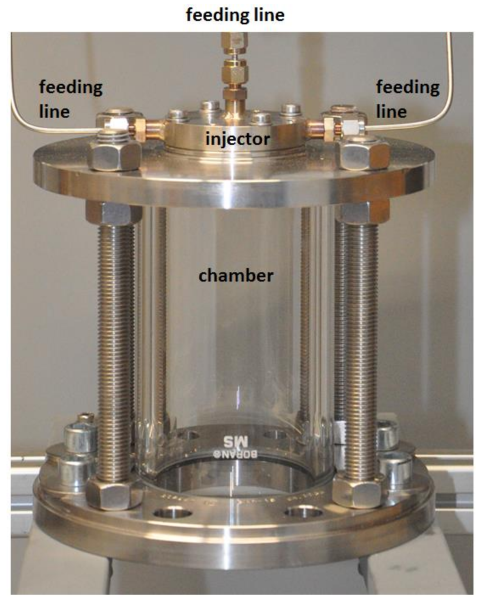

Fig. 7. HIT reaction chamber

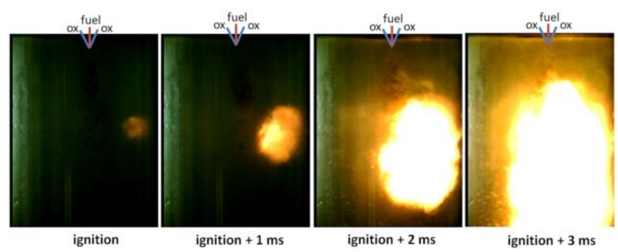

Fig. 8. Ignition of Block 0 and hydrogen peroxide

2.2.3. *Ramjet and SCRamjet Research*

2.2.3.1. *History of M11.1 and Introduction*

During mid of the 1980's the main focus of research at M11 shifted to air vitiator facilities for ram- and SCRamjets [33]. One of the main reasons for this transition was due to the upcoming Hypersonic Technology Program (HTP). The goal of this program was to design a ramjet / turbojet propelled two stage to orbit (TSTO) vehicle called "Saenger II" [34] (see Fig. 9).

Fig. 9. TSTO "Saenger II" concept, from [31]

The last air vitiator development stage of this period at DLR's Lampoldshausen site was an in-house developed chemical air vitiator with a mass flow rate of 5 kg/s. This air vitiator is still in use today at test position M11.1 after an extensive refurbishment and modification phase between 2011 and 2015. It features 11 hydrogen / oxygen burners that heat up pressurized air. The air vitiator can provide boundary conditions up to a 1500 K stagnation temperature, a 25 bar stagnation pressure and up to a 5 kg/s mass flow rate (see Fig. 10).

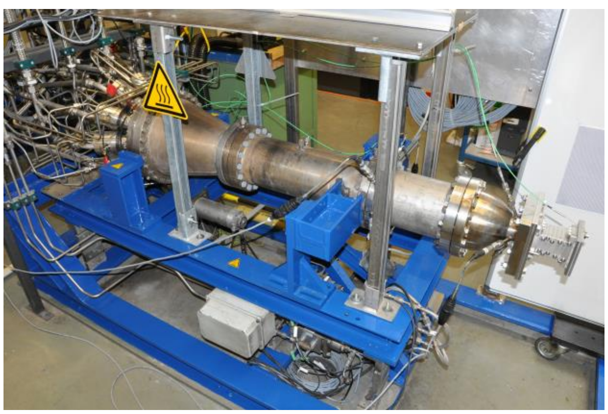

Fig. 10. air vitiator facility M11.1

The air vitiator is controlled by a Siemens® Simatic 7 SPS control system which monitors red line definitions, the selected pre-pressures for the supplies, and the test run sequences. The hydrogen/oxygen burners can be selected in groups from 1 to all 11 burners and features exchangeable sonic orifices in their burner heads to further adjust them to the requirements of the experimental main flow test conditions. This includes also stagnation temperatures as low as 500 K, 1.5 bar stagnation pressure and 0.5 kg/s mass flow. With this versatility the experimental portfolio of the M11.1 air vitiator facility includes hypersonic flight ramjet / scramjet experiments as well as nozzle testing, material testing and cooling experiments, where the air vitiator provides a cost effective way to simulate the vitiation gases of a rocket engine.

The following paragraphs show examples of the experimental variety of the air vitiator test bench M11.1.

2.2.3.2. *Ramjet and Scramjet Research*

From 2016 to 2018, an extensive test campaign was performed including more than 1 000 hot runs at the air vitiator facility. The research topic of this campaign was the applicability of transpiration cooling systems to a model scramjet combustion chamber including different types of porous wall materials (sintered steel and CMC ceramics) and coolants (nitrogen and hydrogen) at various test boundary conditions. In a transpiration cooling system coolant enters the hot gas main flow through a porous wall section, which provides direct cooling to the wall. Additionally this system provides a coolant film / coolant boundary layer to the downstream wall surface for a limited run length. This cooling approach is a promising method to control the high heat loads on internal engine surfaces, which is one of the main challenges connected to high speed flight propulsion. Some unique gas dynamic behavior is caused by the introduction of a coolant secondary flow into the hot gas main flow.

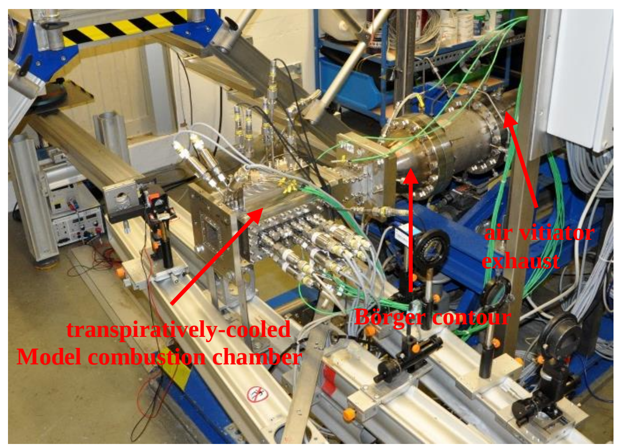

Fig. 11. SCRamjet model combustion chamber test setup

This includes extensive shock-shock and shock-boundary layer interaction (SBLI) phenomena if a wedge shaped shock generator / flame holder is introduced, as well as thermal choking, unstart and, in case of non-inert coolants, SBLI induced self-ignition of the coolant.

For this specific campaign the facility was equipped with a geometrical transition section ("D" in Fig. 12 and [36]-[39] for details) attached to the air vitiator that proceeds ("A","B" and "C" in Fig. 1) from a diameter of 135 mm to a 45 mm x 45 mm square section. The flow was accelerated by a supersonic nozzle ("E" in Fig. 12) to an internal Mach number of 2.5, which corresponds to a flight Mach number of approx. 5.5 to 6.

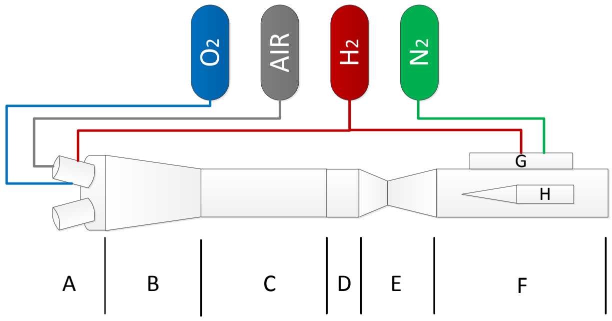

Fig. 12. M11.1 test bench scheme

Downstream of this nozzle a versatile scramjet 300 mm long model combustion chamber was attached ("F" in Fig. 12). This combustion chamber featured a plenum ("G" in Fig. 9) for homogenous coolant distribution of a porous section (100 mm x 30 mm, maximum thickness 20 mm) at the upper wall, supplied with gaseous coolant (hydrogen or nitrogen)

Depending on the test configuration used, different optical accesses, measurement inserts and a horizontally positionable wedge shaped shock generator were used at the model combustion chamber.

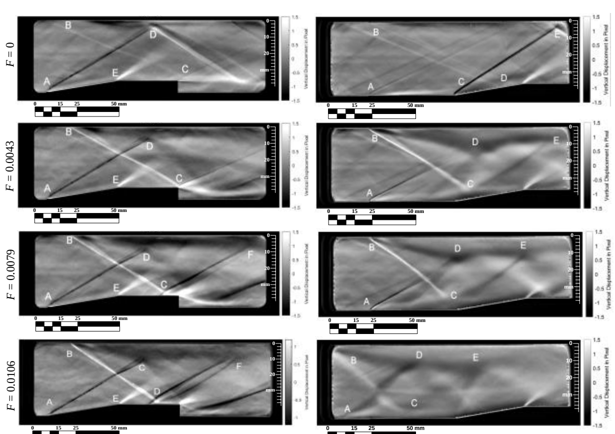

Fig. 13. Typical SBLI pattern (1200 K, 10 bar stagnation values), wall material: Sika-R 150, BOS images

This shock generator ("H" in Fig. 12, length 80 mm, width 44 mm, 9.3° ramp angle) could be freely positioned in the horizontal plane of the lower wall by a pressure tight positioning mechanism.

Advanced optical measurement techniques such as background oriented schlieren (BOS) using an in-house developed code and high-speed BOS were applied to visualize the flow field (see Fig. 13).

The test campaign proved a strong influence of the shock generator and its position on the flow field, which reduced the cooling efficiency up to 20-25 %. Additionally hydrogen was identified as a superior coolant that provides sufficient cooling efficiency even in strong interactions in the flow field. However it is prone to self-ignition during certain boundary conditions. Details on those experiments and recent results can be found e.g. in references [36-39].

2.2.3.3. *Film Cooling Research*

During 2018 and 2019 the test runs for an ESA GSTP program addressing liquid film cooling in small rocket engines were conducted. This program, called "ExLiFiCo" [40], included several international partners: ESA ESTEC Noordwijk (NL), ArianeGroup Ottobrunn (GER), Numeca Brussels (BE), VKI Von Kármán Institute of Fluid Dynamics, Brussels (BE) and DLR Institute of Space Propulsion, Lampoldshausen (GER).

The experiments were conducted in the lower operational range of the air vitiator facility (500-600 K, 0.5-1.4 kg/s, 2 bar stagnation values). The air vitiator provided the boundary conditions for an experimental film cooling chamber with various optical accesses (see Fig. 14) and a film injector. Ethanol was used as a substitute for hazardous hydrazine fuels to simulate the coolant.

In summary more than 250 test runs were performed during this campaign with measurement techniques including background oriented schlieren (BOS) and laser induced fluorescence (LIF) specially tailored to the requirements of the experiment (see [40] for details).

2.2.3.4. Outlook on Future Hypersonic Research

Future projects include material tests, a continuation of the transpiration cooling experiments on scramjets and nozzle tests.

The transpiration cooling experiments will include a combustion process in the main flow to further investigate the applicability of such systems in scramjets if an additional combustion process is present. This is necessary since the pressure distribution of the flow field and the shock pattern will significantly change by the additional interference with the combustion / flame zone.

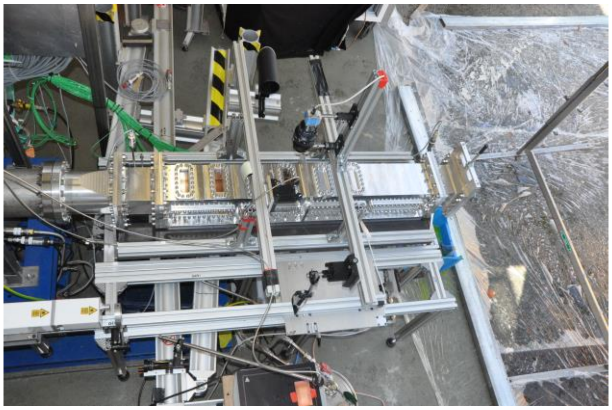

Fig. 14. ExLiFiCo film cooling experiment with LIF setup attached to M11.1 air vitiator

Furthermore the test facility will be updated to accommodate additional advanced optical measurement techniques such as 3D BOS and for extended runtime at high stagnation temperatures.

2.2.4. *Gel Propulsion*

2.2.4.1 Background and Infrastructure

In general, gels are homogeneous mixtures of a base fluid and a gelling agent which usually have a yield point. Gelled propellants offer the potential to build propulsion systems with a thrust throttling and control capability, easy handling, good storage characteristics and an improved operational safety [41].

Furthermore, gelling enables the designer to tailor the propellant with respect to the mission requirements by adding e.g. particles of metal, a catalyst or other energetic materials without the risk of sedimentation or separation. The beneficial combination of both performance flexibility and storability merges major advantages of liquid and solid propulsion systems and is caused by the non-Newtonian flow behavior of gels. Potential applications are controllable rocket motors for various missiles or sounding rockets, gas generators, thrusters of reaction control systems, as well as specific applications in e.g. ducted rockets or ramjet propulsion systems.

General information about gel propulsion and a summary of the status of worldwide activities in the year of publication is, amongst other papers, given in the overview reports in Refs. [42] and [43].

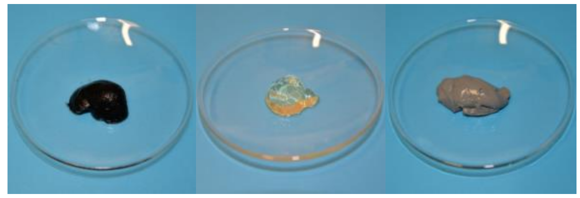

Fig. 15. Examples of different gel propellant samples.

At the Institute of Space Propulsion of the German Aerospace Center in Lampoldshausen investigations on environmentally friendly and simply producible gels with advanced combustion and performance characteristics are conducted. Here, the main goal is to obtain a detailed knowledge of the processes within combustion chambers, injectors and feed lines. This shall enable the realization of reliable design processes for future gel rocket motors with high power densities and stable operating envelopes at reduced costs and a small demand for testing. The activities are performed in close cooperation with industry and other research institutions and are embedded in the Space as well as Defense & Security research at DLR.

The test position M11.4 is exclusively used for the investigations of the combustor processes such as injection, atomization, evaporation and combustion of gelled propellants. The gelled propellants are stored in cartridges, which are easily exchangeable piston-type accumulators. 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. Although this approach does not reflect any flight configuration, it allows a detailed analysis of the performance characteristics of various gel formulations. A H_2/O_2 torch igniter starts the combustion reliably and smoothly. Additionally, the combustion may be boosted by an auxiliary oxygen injection. 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 H_2O at up to 200 bar. A comprehensive measurement instrumentation including thrust, pressures and temperatures as well as optical diagnostics is present.

The laboratory at M3 (Fig. 16) is of central importance concerning the research and characterization of new and optimized gel compositions. The emphasis is on chemical analysis, development and prequalification of new advanced propellants or fuels and oxidizers. For this purpose, the M3 laboratory wing is equipped with a large number of different analytical instruments, ranging e.g. from trace metal analytics to comprehensive surface analysis. This opens up comprehensive new perspectives for the fundamental understanding of the propellants' chemistry in the solid, liquid or gaseous state as well as its physical properties at different loads.

Fig. 16. Part of the physical-chemical laboratory at M3.

Propellants, which may be subject of the German Explosives Law, can be prepared, handled and analyzed in a dedicated production facility adjacent to the test complex M11. The amounts of fuel or oxidizer produced are placed on a lab-scale and up to 2.5 kg TNT equivalent are allowed. Two dissolver apparatuses are available for the production of various gelled or particle-loaded compounds. The dissolvers are particularly suitable for the production of particulate gels due to their capability to generate the high shear rates necessary to disperse e.g. metal particles and the gelling agents.

2.2.4.2 Combustion and Performance Testing

A set of modular, capacitively cooled combustion chambers with different diameters and lengths is utilized for assessing the combustion performance of new gel propellants. In the past, a cylindrical combustion chamber with an inner diameter of 21 mm (called BK21) was used for comprehensive investigations on the optimum ratio of combustion chamber volume and nozzle throat area V_c/A_t i.e. the optimum characteristic length L* of the combustor. Results were compared to data obtained with a larger chamber featuring an inner diameter of 50 mm (BK50). With the smaller combustion chamber and for the monopropellant gel under investigation at this time, an optimum L* of 1.5 m for 70 bar combustion chamber pressure and 1.8 m for 50 bar was determined, albeit a minimum pressure of 40 bar was required for a stable and self-sustained combustion. In contrast, hot fire tests with the BK50 showed lower combustion efficiency with an optimum characteristic length of approx. 7.5 m but with an extended operational pressure range. The enhanced efficiency was attributed to beneficial spray-wall-interactions increasing the heat exchange within the evaporation-driven combustion process [44,45].

To analyze the effect of spray-wall-interactions, additional combustion chambers BK20, BK30 and BK40 with 20 mm, 30 mm and 40 mm inner diameter, respectively, were designed, built and tested. By their handy and versatile design, featuring additional pressure sensors and wall temperature measurements, these combustion chambers became very valuable for characterization of combustion and performance. Actually, BK40 is by now used as reference configuration for the comparison of different gel formulations at DLR. It also serves as the base for derivates e.g. for the investigations on gelled bipropellants (BK40ZS)

The vertical test stand (VTS) at M11.4 allows the investigation on the behavior and performance of metallized and other particle-loaded propellants under application-relevant conditions. A hot fire test at the VTS with an Aluminum-loaded propellant is shown in Fig. 17. The stand enables testing of versatile propellants reducing the risk of depositions in the combustion chamber and the risk of a clogging of the nozzle. This configuration has significantly enhanced the test capabilities for gelled propellants in Lampoldshausen.

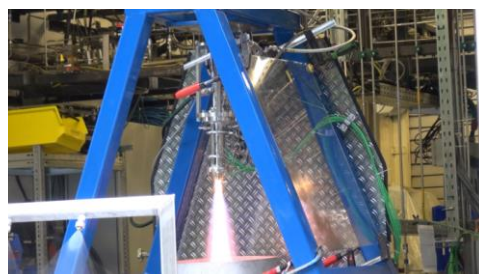

Fig.17. Combustion chamber BK40 is fired at vertical test stand with Al-loaded monopropellant.

At the German Aerospace Center (DLR) mainly gelled monopropellants were investigated during the last years. Gelled monopropellants consist of two or more components, which are the fuel/propellant blend, at least one gelling agent and for most propellants also additives.

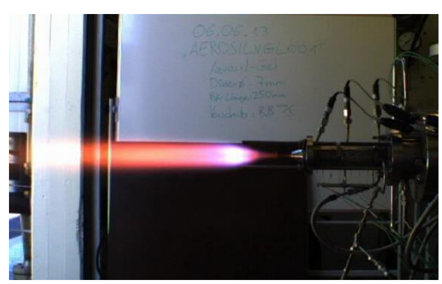

Fig. 18. Hot fire test with Aerosil-based gel.

For the selection of suitable gel propellant compositions, reasonable performance, production, handling and treatment properties must exist or must be developed. Thereby, an important element of the propellant development in Germany is the – as far as possible – avoidance of harmful substances. This means amongst others that toxicity of the propellants and the sensitivity to shock and friction shall be as low as possible.

Gelling agents like organic gelators (gelatine, agar, etc.) and inorganic particles (Aerosil®, CAB-O-SIL®,) have been tested at first [46,47]. For rheological experiments, also Cellosize™ and Thixo 2 have been used in [48], as well as Carbopol®. For the monopropellants, our focus was then set on compounds with Carbon-based particulate and commercial urea-based gellants. These gel propellants feature high performance and good delivery characteristics with less than 8% of admixtures.

2.2.4.3 Hypergolic Bipropellant Gels

The ignition and combustion behavior and the energy content may be modified by the addition of metal particles (e.g. µ- and Nano-Al) or other energetic materials [48]. Some prior tests at ramjet-relevant conditions indicated that there may hardly be a positive effect on the combustion efficiency by the adding of aluminum since the oxidation might be very limited under the given conditions [49]. Otherwise, nano-particles of silver, platinum and manganese oxide were tested and successfully used to reduce ignition delay times of the hypergolic ignition to less than 10 ms for a bipropellant system based on gelled N,N,N′,N′-Tetramethylethylenediamine (TMEDA) and High Test Peroxide [50].

Bipropellant gels and especially green hypergolic systems moved back into research focus only recently. Though a bipropellant system is more complex than a monopropellant system, it bears many advantages like higher specific and density impulses, better safety characteristics in terms that oxidizer and fuel are neither premixed nor that energy might be released through an unwanted exothermic chemical decomposition process in the tank, and it does not require an additional ignition system if the fuel/oxidizer combination is hypergolic. In order to identify possible fuels and oxidizers for a green, easy to handle and storable hypergolic propellant system a set of criteria based on GHS hazard sentences was used [51]. Two potential oxidizers were identified: hydrogen peroxide (H_2O_2) and white fuming nitric acid (WFNA). Preliminary studies also proofed sufficient gelation of both candidates using e.g. Aerosil® (see Fig. 19).

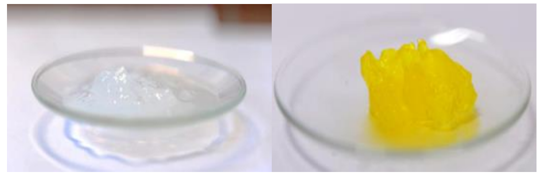

Fig. 19. Gelled hydrogen peroxide (left) and gelled nitric acid (right).

Fig. 20. Hypergolic reaction of Tetramethylethylenediamine TMEDA gel with HTP (sequence from high speed video recording).

However, hydrogen peroxide is preferred as oxidizer due to a higher performance and more environmentally friendly exhaust gases. The group of liquid methylated diamines was identified as promising high performance fuels candidates. However, in order to enable hypergolic reaction with hydrogen peroxide, an additional catalyst, such as a transition metal compound or a strong reducing agent, is needed.

To quickly test a large number of fuel/catalyst combinations, a simple drop test experiment was implemented. In this setup the oxidizer – here, 98% peroxide– is dropped from a specific height into a vial with fuel gel. By means of filming the reaction with a high speed video camera, the ignition delay times is determined. Fig. 20 shows screen shots from a typical test run.

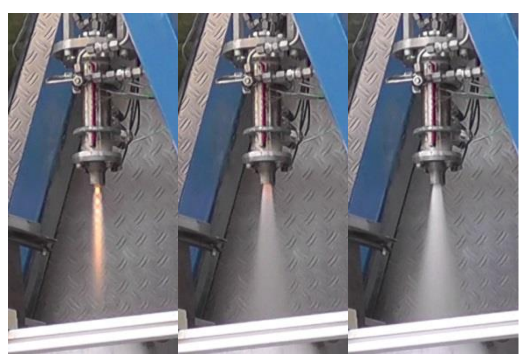

Fig. 21. Sequence from an ignition test of a novel particle free gelled monopropellant.

With this setup various combinations of methylated diamine gels and hypergolic catalysts were assessed and aforementioned N,N,N′,N′-Tetramethylethylendiamine (TMEDA) hypergolically activated with copper-(II)-chloride was identified as a very promising fast igniting fuel for combinations with HTP [52]. Further tests both on content und type of the catalyst are carried out. In parallel, a dedicated bipropellant model combustor setup has been designed and manufactured. First ignition and hot fire tests will be conducted at M11.4 near-term in order to verify the test results achieved in laboratory.

Most recent research on monopropellant gel addresses requirements for special applications. For the purpose of optical investigations on injection, atomization and flame structure of gelled propellants new particle free gel compositions are in development (Fig. 21). Such a gel may also be useful for applications like gas generators and reaction control systems. In contrast, for the use in booster and sustainer stages also metallized “high-performance” propellant gels were tested lately. Another focus of current work is the development of monopropellant gels with high insensitivity and/ or extended operational envelope. Here, great progress was made by use of ionic liquids [53].

2.2.4.4 Optical Analyses of Gel Combustion Chamber Processes

Two different model combustion chamber designs with windows are available allowing access for optical diagnostic tools and enabling the visualization and detailed investigation of the processes in the combustor. Preliminary tests with a round chamber demonstrated the feasibility and the benefits of a visual examination of the gel injection and combustion using e.g. shadowgraph technique [44]. Taking into account experiences from these tests regarding field of view and fouling of the windows, a modular rectangular chamber was designed, manufactured and successfully deployed [54].

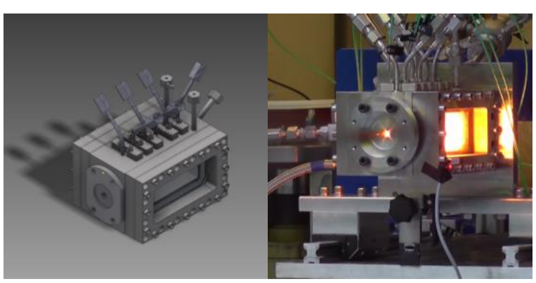

Fig. 22. Rectangular gel rocket combustion amber with optical access (left: sketch; right: hot fire test).

The rectangular combustor with optical access as shown in action right-hand-side in Fig. 22 is made of stainless steel and features both an interchangeable nozzle and a changeable single injector. For the window, sapphire was chosen due to its superior mechanical and thermal properties. The sapphire window is preinstalled in a metallic frame simplifying the handling at the test facility and reducing changeover times in between tests. The design is also very versatile with respect to test configurations since the sapphire can easily be replaced by metallic elements, dedicated measurement segments or material samples. With the exception of a nitrogen purge / film cooling system for reducing the deposition of soot on the window and to limit the heat loads during start-up, no active cooling is foreseen. This limits the test time to a few seconds.

Optical investigations carried out comprise so far shadowgraph and true image video recordings using either a general purpose industrial camera or a high speed black-and-white camera. Different filters were applied where appropriate. Snapshots out of the recorded high speed videos from the ignition of the gel propellant (boosted with gaseous oxygen) are given in Fig. 23. The image indicates the zone, where the auxiliary oxygen and the gelled propellant react during the start-up phase. Otherwise, analysis of the flame pattern has been found difficult due to recirculation zones and radiation from soot coming from the carbon-based monopropellant gel used for these tests. Here, new and more significant results are expected once the new particle free propellants are fully characterized and available in in sufficient quantity.

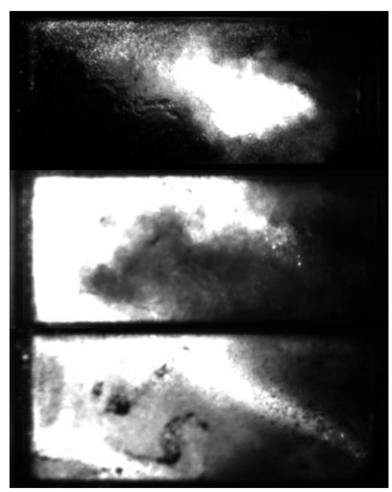

Fig.23. Gel ignition, sequence from high speed camera recordings (flow direction from right to left).

3. CONCLUSION

Fundamental scientific research is carried out at test complex M11 in several different areas ranging from long-term storable monopropellants for satellite applications via green hypergolic and high performance bipropellants for microlauncher-upper-stages or apogee motors as well as gelled rocket combustion and engines for small launcher developments. Furthermore, air breathing hypersonic flows, combustion and cooling possibilities are in investigated. Besides DLR projects, tests for European and ESA research programs, research partnerships as well as industry cooperations are conducted at M11. Test Complex M11 offers a unique infrastructure and possibilities for investigations on future propellants and propulsion systems for orbital and satellite applications throughout Europe.

4. ACKNOWLEDGEMENTS

The authors would like to thank the M11 and the laboratory team wholeheartedly. Without their support, usually done in the background, neither the lots of test campaigns, nor the excellent research and development results could be gained. Thank you!

5. REFERENCES

[1] Ciezki, Helmut & Werling, Lukas & Negri, Michele & Strauss, Friedolin & Kobald, Mario & Kirchberger, Christoph & Freudenmann, Dominic & Hendrich, Christian & Wilhelm, Marius & Petrarolo, Anna & Schlechtriem, Stefan. (2017). 50 Years of Test Complex M11 in Lampoldshausen – Research on Space Propulsion Systems for Tomorrow.

[2] Kobald, M., and Petrarolo, A., "Combustion Visualization and Characterization of Liquefying Hybrid Rocket Fuels," 51st AIAA Joint Propulsion Conference, Orlando, FL, USA, 2015.

[3] Schüttauf, K., Stamminger, A., Lappöhn, K., Ciezki, H.K., and Kitsche, W., "Operation of solid rockets in comparison with hybrid rockets during the STERN project," 14th Int. Conference on Space Operations, Daejeon, Republic of Korea, May16-20, 2016.

[4] Kirchberger, C., Ciezki, H.K., Hürttlen, J., Schaller, U., Weiser, V., Caldas-Pinto, P., Ramsel, J., and Naumann, K.W., "An Overview of the German Gel Propulsion Technology Program," ID 3124839, Proceedings of 5th Space Propulsion Conference, May 2-6, 2016, Rome, Italy.

[5] Sackheim, R. L., and Masse, R. K., "Green Propulsion Advancement: Challenging the Maturity of Monopropellant Hydrazine," *Journal of Propulsion and Power*; Vol. 30, No. 2, 2014, pp. 265–276. doi: 10.2514/1.b35086.

[6] Sutton, G. P., and Biblarz, O., *Rocket propulsion elements*, 8th edition., John Wiley & Sons; Wiley, Hoboken, N.J, 2010.

[7] European Chemicals Agency, "Candidate List of substances of very high concern for Authorisation: published in accordance with Article 59(10) of the REACH Regulation," http://echa.europa.eu/en/candidate-list-table, [retrieved 17 August 2018].

[8] Gregory, M., Fisher, D. J., Mungas, C., and Carryer, B., *Nitrous Oxide Fuel Blend Monopropellant, US 2009/0133788 A1*, 10. Nov. 2008.

[9] Mungas, G., Vozoff, M., and Rishikof, B., "NOFBX: A new non-toxic, Green propulsion technology with high performance and low cost," *63rd International Astronautical Congress, 1-5 October 2012, Naples, Italy*, 2012.

[10] Taylor, R., "Safety and Performance Advantages of Nitrous Oxide Fuel Blends (NOFBX) Propellants for Manned and Unmanned Spaceflight Applications," *A safer space for a safer world*, edited by L. Ouwehand, ESA Communication, Noordwijk, 2012.

[11] Firestar Technologies, L. L.C., "NOFBX™ Systems," http://www.firestar-engineering.com/NOFBX-MP.html, [retrieved 3 September 2019].

[12] Qingguo, L., Xin, Q., Yuanding, W., and Bo, Q., "R&D of green propellant engines for space propulsion systems," *Space Propulsion Conference 14.-18.05.2018, Sevilla, Spain*.

[13] Mayer, A. E.H.J., Waugh, I., and Poucet, M., "European Fuel Blend, Final Report: ESTEC Contract Number 4000113544/15/NL/AD," TNO 2018 R10640, 8 Jun. 2018, https://artes.esa.int/projects/european-fuel-blend-development, [retrieved 3 September 2019].

[14] Mayer, A. E.H.J., Wieling, W.P.W., Watts, A., Poucet, M., Waugh, I., Macfarlane, J., and Valencia-Bel, F., "European Fuel Blend development for in-space propulsion," *Space Propulsion Conference 14.-18.05.2018, Sevilla, Spain*.

[15] Waugh, I., Moore, E., Macfarlane, J., Watts, A., and Mayer, A. E.H.J., "Testing of a novel nitrous-oxide and ethanol fuel blend," *Space Propulsion Conference 14.-18.05.2018, Sevilla, Spain*.

[16] Ciezki, H. K., Zhukov, V., Werling, L., Kirchberger, C., Naumann, C., Friess, M., and Riedel, U., "Advanced Propellants for Space Propulsion – A Task within the DLR Interdisciplinary Project "Future Fuels"," *8th European Conference for Aeronautics and Space Sciences (EUCASS), 1.-4. July 2019, Madrid, Spain*.

[17] Wilhelm, M., Hendrich, C., Zimmermann, H., Ciezki, H., and Schlechtriem, S., "Test Facility for Research on Advanced Green Propellants under High-Altitude Conditions," *Space Propulsion Conference 14.-18.05.2018, Sevilla, Spain*.

[18] Gruss, M., "DARPA Scraps Plan To Launch Small Sats from F-15 Fighter Jet," http://spacenews.com/darpa-airborne-launcher-effort-falters/, [retrieved Abgerufen am: 15 February 2018].

[19] Kick, T., Starke, J. H., and Naumann, C., eds., *Green Propellant Substituting Hydrazine: Investigation of Ignition Delay Time and Laminar Flame Speed of Ethene/Dinitrogen Oxide Mixtures*, 2017.

[20] Naumann, C., Kick, T., Methling, T., Braun-Unkhoff, M., and Riedel, U., "Ethene / Dinitrogen Oxide - A Green Propellant to substitute Hydrazine: Investigation on its Ignition Delay Time and Laminar Flame Speed," *26th International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS), July 30 - August 4, 2017, Boston, USA*, 2017.

[21] Naumann, C., Janzer, C., and Riedel, U., "Ethane / Nitrous Oxide Mixtures as a Green Propellant to Substitute Hydrazine: Validation of Reaction Mechanism," *9th European Combustion Meeting (ECM), 14.-17.04.2019, Lisbon, Portugal*.

[22] Werling, L., Lauck, F., Freudenmann, D., Röcke, N., Ciezki, H., and Schlechtriem, S., "Experimental Investigation of the Flame Propagation and Flashback Behavior of a Green Propellant Consisting of N2O and C2H4," *Journal of Energy and Power Engineering*; Vol. 11, No. 12, 2017. doi: 10.17265/1934-8975/2017.12.001.

[23] Werling, L., Jooß, Y., Wenzel, M., Ciezki, H. K., and Schlechtriem, S., "A premixed green propellant consisting of N_2O and C_2H_4: Experimental analysis of quenching diameters to desing flashback arresters," *International Journal of Energetic Materials and Chemical Propulsion*; Vol. 17, No. 3, 2018, pp. 241–262. doi: 10.1615/IntJEnergeticMaterialsChemProp.2019027950.

[24] Werling, L., Hassler, M., Lauck, F., Ciezki, H. K., and Schlechtriem, S., "Experimental Performance Analysis (c* & c* Efficiency) of a Premixed Green Propellant consisting of N2O and C2H4", *53rd AIAA/SAE/ASEE Joint Propulsion Conference, 10th - 12th July 2017, Atlanta, GA, USA*, 2017.

[25] Werling, L., Bätz, P., Ciezki, H., and Schlechtriem, S., "Influence of combustion chamber size (L*) on characteristic exhaust velocity (c*) for a N2O/C2H4 premixed green propellant," *Space Propulsion Conference, 14th - 18th May 2018, Seville, Spain.*

[26] Werling, L., Hörger, T., Ciezki, H. K., and Schlechtriem, S., "Experimental and Theoretical Analysis of the Combustion Efficiency and the Heat Loads on a N2O/C2H4 Green Propellant Combustion Chamber," *8th European Conference for Aeronautics and Space Sciences (EUCASS), 1st - 4th July 2019, Madrid, Spain*.

[27] Perakis, N., Werling, L., Ciezki, H., and Schlechtriem, S., "Numerical Calculation of Heat Flux Profiles in a N2O/C2H4 Premixed Green Propellant Combustor using an Inverse Heat Conduction Method," *Space Propulsion Conference, 1st - 5th May 2016, Rome, Italy*.

[28] Lauck, F., Negri, M., Wilhelm, M., Freudenmann, D., Schlechtriem, S., Wurdak, M. and Gotzig, U., „Test bench preparation and hot firing tets of a 1 N hydrogen peroxide monopropellant thruster," *Space Propulsion Conference,* 2018, *Seville, Spain*.

[29] Gotzig, U., Wurdak, M., Lauck, F., Development of a Flight Type 1N Hydrogen Peroxide Thruster, *Space Propulsion Conference, 2018, Seville, Spain.*

[30] Lauck, F., Negri, M., Freudenmann, D. and Schlechtriem, S., „Selection of Ionic Liquids and Characterization of Hypergolicy with Hydrogen Peroxide," *11th ISICP, 2018, Stuttgart, Germany*.

[31] Lauck, F., Negri, M., Freudenmann, D. and Schlechtriem, S., „Study on hypergolic ignition of ionic liquid solutions," *8th European Conference for Aeronautics and Space Sciences (EUCASS),* 2019, *Madrid,* Spain.

[32] Lauck, F., Witte, J., Negri, M., Freundenmann, D. and Schlechtriem, S., „Design and first results of an injector test setup for green hypergolic propellants," *AIAA Propulsion and Energy Forum,* 2019, *Indianapolis, USA*.

[33] Ciezki, H., Werling, L., Negri, M., Strauss, F., Kobald, M., Kirchberger, C., Freudenmann, D., Hendrich, C., Wilhelm, M., Petrarolo, A., Schlechtriem, S., 50 Years of Test Complex M11 in Lampoldshausen – Research on Space Propulsion Systems for Tomorrow, *7th European Conference for Aeronautics and Space Sciences (EUCASS), 3rd - 6th July 2017, Milano, Italy.*

[34] Bissinger, N. C., Koschel, W., Sacher, P. W., Walther, R., SCRAM-Jet Investigations Within the German Hypersonics Technology Program (1993-1996), in: E. T. Curran, S. N. B. Murthy (Eds.), Scramjet Propulsion, *AIAA Progress in Aeronautics and Astronautics, Vol. 189, American Institute of Aeronautics and Astronautics, 2000, Reston, VA, USA, pp. 119-158.*

[35] Koelle, D. E., Sacher, P. W., Grallert, H., Deutsche Raketenflugzeuge und Raumtransporter-Projekte, in: *Die deutsche Luftfahrt, Vol. 34, Bernard & Graefe, 2007, Bonn, Germany, (In German).*

[36] Strauss, F., General, S., Manfletti, C., Schlechtriem, S., Flow Visualizations with Background Oriented Schlieren in a Transpiration-Cooled Model Scramjet Combustor, *International Journal of Energetic Materials and Chemical Propulsion, 18 No. 2 (2019) 133-155.*

[37] Strauss, F., Witte, J., General, S., Manfletti, C., Schlechtriem, S., Experiments on Nitrogen and Hydrogen Transpiration Cooling in a Model Scramjet Combustor, *AIAA 2018-4932, 9th-11th July 2018 Joint Propulsion Conference, Cincinnatti, OH, USA.*

[38] Strauss, F., General, S., Manfletti, C., Schlechtriem, S., Experimental Flow Path Analysis of a Hydrogen Transpiration Cooled Model Scramjet Combustor, *8th European Conference for Aeronautics and Space Sciences (EUCASS), 1rd-4th July 2019, Madrid, Spain.*

[39] Strauss, F., General, S., Manfletti, C., Schlechtriem, S., Experiments on Nitrogen and Hydrogen Transpiration Cooling in a Model Scramjet Combustor, *AIAA 2019-4015, AIAA Propulsion and Energy Forum, 19th-22nd August 2019, Indianapolis, IN.*

[40] Soller, S., Behr, R., Grauer, F., Claramunt, K., Dinescu, C., Fiorini, D., Peveroni, L., Simonini, A., General, S., Kirchberger, C., Strauss, F., Steelant, J., Experimental and Numercial Investigation of Liquid Film Cooling in Small Rocket Engines, *8th European Conference for Aeronautics and Space Sciences (EUCASS), 1st -4th July 2019, Madrid, Spain.*

[41] Ciezki, H.K., and Naumann, K.W., "Some Aspects on Safety and Environmental Impact of Gel Propulsion," Propellants, Explosives, Pyrotechnics, invited publication for special issue *Insensitive Munitions*, Vol. 41 (3), 2016, pp. 539-547.

[42] Natan, B., and Rahimi, S., "The Status of Gel Propellants in Year 2000", Combustion of Energetic Materials, edited by Kuo, K.K., and DeLuca, L.T., Begell House, New York, pp. 172–194, 2001.

[43] Ciezki, H.K., Naumann, K., and Weiser, V., „Status of Gel Propulsion in the Year 2010 with a Special View on the German Activities," DLRK 2010-1326, *German Aerospace Congress 2010*, August 31 – September 2, 2010, Hamburg, Germany.

[44] Kröger, P., Negri, M., Ciezki, H.K., "Influence of Various Aspects on the Performance Characteristics of Gel Propulsion Systems," Proceedings of *6th European Conference for Aeronautics and Space Sciences (EUCASS2015)*, June 29 – July 3 2015, Krakow, Poland.

[45] Kröger, P., Kirchberger, C., and Ciezki, H.K., "Influence of the Combustion Chamber Geometry on the Performance of a Gel Propulsion System," ID 3124841, Proceedings of *5th Space Propulsion Conference*, May 2-6, 2016, Rome, Italy.

[46] Bohn, M.A., Hürttlen, J., Menke, K.,Roth, E., and Weiser, V. „Entwicklung und Charakterisierung umweltfreundlicher Geltreibstoffe für schubgeregelte Raketenantriebe." *German Aerospace Congress 2008*, September 23-25, 2008, Darmstadt, Germany..

[47] Louaze, G., Caty, F., Weiser, V., and Roth, E, "Influence of Aerosil on the combustion of gelled nitromethane," *Proc. of 38th Int. Annual Conference of ICT*, 2007, Karlsruhe, Germany, pp. 92/1-92/11.

[48] Stiefel, A. D., Kirchberger, C. U., Ciezki, H. K., Kurilov, M., Kurth, G., "The Flow of Gels through a Nozzle like Geometry." *International Journal of Energetic Materials and Chemical Propulsion.* Begell House. ISSN 2150-766X, 2019

[49] Tepper, F., and Kaledin, L., "Combustion characteristics of kerosene containing Alex® nano-aluminum," Proceedings of the *5th Int. Symposium on Special Topics in Chemical*

Propulsion (5-ISICP), June 18−22, 2000, Stresa, Italy.

[50] Negri, M., and Ciezki, H.K., "Combustion of Gelled Propellants Containing Microsized and Nanosized Aluminum Particles," AIAA *Journal of Propulsion and Power*, Vol. 31, No. 1, 2015, pp. 400–407.

[51] Ricker, S. , Kurilov, M., Freudenmann, D., Kirchberger, C., Hertel, T., Ciezki, H., and Schlechtriem, S., „Novel gelled fuels containing nanoparticles as hypergolic bipropellants with HTP", Proceedings of *8th European Conference for Aeronautics and Space Sciences (EUCASS2019)*, July 1 – 4 2019, Madrid, Spain.

[52] Kurilov, M., Kirchberger, C., Stiefel, A., and Ciezki H. K., „A Method for Screening and Identification of Green Hypergolic Bipropellants." *International Journal of Energetic Materials and Chemical Propulsion*. Begell House. ISSN 2150-766X, 2018.

[53] Kirchberger, C., Freudenmann, D., and Ciezki H.K., "Influence of Propellant Composition on the Performance of a Gel Rocket Combustion Chamber," AIAA-2019-4428, AIAA Joint Propulsion and Energy 2019 Forum, 19-22 August 2019, Indianapolis, IN, USA.

[54] Kirchberger, C., Kröger, P., and Ciezki H.K., "Design and Run-In Tests of a Gel Combustion Chamber with Optical Access," AIAA-2017-5068, 53th AIAA Joint Propulsion Conference, 10-12 July 2017, Atlanta, GA, USA.