# Test Facility for Research on Advanced Green Propellants under High-Altitude Conditions

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**KEYWORDS:**

Subatmospheric Testing, Test Complex M11, Propellant Research, Hydrazine Replacements, Green Advanced Propellants

**ABSTRACT*:***

A test facility for research on green advanced propellants under subatmospheric conditions has been designed and built at test complex M11. The facility is capable of testing various green advanced propellants for satellite and orbital propulsion applications with focus on research requirements. High flexibility in using different propellants and propellant combinations, in control and measurement equipment and in test conduction are key aspects for operation of the test facility. An overview of the test facility itself and the conducted tests are given.

## 1. Introduction

Restrictive laws like the EU REACH regulation, tightened safety standards during handling and fueling of launcher and satellite propulsion systems as well as environmental concerns lead to increasing research into propellants to replace hydrazine and its derivatives. To date a multitude of so called "green" propellants, i.e. propellants with comparable properties to hydrazine but less toxicity and reduced environmental impacts, have been designed and investigated. Advanced liquid monopropellant candidates are based on concentrated hydrogen peroxide, mixtures of oxidizers and fuels (e.g. nitrous oxide and ethylene), solutions of energetic compounds of ammonium dinitramide (ADN; e.g. LMP-103S) or hydroxylammonium nitrate (HAN; e.g. AF-M315E) or energetic ionic liquids. [1, 2, 3]

Depending on the hydrazine substitute unconventional phenomena can occur and need to be analyzed for orbital propulsion applications. In particular, liquid premixed monopropellants tend to cavitate when high negative pressure gradients occur like in orifice flows or when injecting propellants into near-vacuum environments. Contrary to single substance propellants cavitation or flashing of multicomponent propellants can lead to segregation effects thereby affecting propellant feeding, injection, ignition and combustion processes [4]. For multicomponent propellants containing dissolved solid substances (e.g. energetic salts) segregation can also cause clogging of the feed system and at worst to the loss of the whole propulsion system. [4, 5, 6]

DLR's Institute of Space Propulsion realized the need to investigate these phenomena in engines running on advanced green propellants. Moreover, the propellant behaviors themselves are investigated at relevant conditions for orbital propulsion applications. For that reason the test facility M11.2 was planned, designed and set up for research on green propellants under high-altitude conditions.

## 2. General Information on High-Altitude Test Facility M11.2

The key aspect during the definition phase of the test facility M11.2 was its ability to conduct tests on a broad variety of propellants and propellant combinations without the need for major modifications and time consuming backfittings. This ability is necessary because space for test facilities is limited at test complex M11. A single facility for a multitude of propellants seems more complicated compared to several separate test positions and thereby more expensive. However, in total it is even more cost efficient. Infrastructure and installations like pressure regulators or actuators are only required once and just need to be extended. Complexity is additionally reduced by the converging requirements for orbital propulsion systems, e.g. thrust classes, electrical supplies or feeding system concepts. In addition operational costs are reduced given that the facility runs at a higher capacity. Besides the variety in use of propellants enables scientific research possibilities and supplements the research areas at test complex M11.

A second focus in the definition phase was laid on research possibilities and adaptability. Research, especially at low Technology Readiness Levels (TRL), is a highly dynamic process during which a lot of parameters are varied, ranging from physical parameters, geometrical designs, utilized materials and construction methods, priming and ignition methods to startup and shutdown procedures. This aspect should be included and best possible conditions should be created at the test facility. In fact, M11.2 offers excellent possibilities for cold flow spray testing, ignition investigations and steady-state thruster hot-firings. Experiments can be conducted under subatmospheric environment below 3 mbar as well as at atmospheric pressure levels. Theoretically, testing under special gas atmospheres would be feasible as well.

Another aspect of M11 is ignition research of advanced green propellants. Hence M11.2 is equipped with different systems and installations for the realization of ignition investigation of monopropellants, bipropellants and hypergols. Possible system options include electrical ignitions via high currents, or high voltages, or ignition via pilot flame igniters driven by e.g. gaseous hydrogen and oxygen at variable mixture ratios and output powers. Hypergolic and catalytic ignition systems can be supported for example by regulating valves or heaters.

## 3. M11.2 Infrastructure

This section gives a detailed description of the test facility and its components. Focus is laid on the vacuum generating equipment, the test facility's supplies as well as on the measurement and control system.

*Figure 1. View on the vacuum chamber and the ejector-diffusor system of test facility M11.2*

### 3.2. Vacuum Generation System

The vacuum generation system is one of the main systems of the high-altitude test facility M11.2. Nevertheless it enables atmospheric testing as well. The vacuum system consists of a vacuum chamber, mechanical and fluidic vacuum pumps, an inserted exhaust gas diffusor and a vacuum slide

#### 3.2.1. Vacuum Chamber

The vacuum chamber is a two-sectioned stainless steel chamber with a total volume of 4.2 m³ and a rail-mount moveable chamber lid (Figure 2). The first compartment includes about one third of the total volume and can be seen in Figure 4**.** The compartments are divided by a separator element that enables the installation of an exhaust gas diffusor and an auxiliary nitrogen nozzle. The smaller compartment houses the injector, experimental combustor or thruster when the chamber is closed. For installation, modification or storage the chamber lid can be opened and rolled inside the building where it is additionally protected from environmental effects. The second section includes spray nozzles to cool down the exhaust gases before it is sucked off by the pumps. At the bottom of the second compartment condensate collectors are installed. Two connections in the second part are reserved for the vacuum pumps and the ejector-diffusor unit. At the connection of the latter one a full flow vacuum slide is installed.

*Figure 2. Opened vacuum chamber lid with base frame for thruster installation*

Moreover, the vacuum chamber is the interface of every connection to or from the research thruster. All interfaces need to be vacuum sealed. The main interface is located at the center of the chamber lid, seen in Figure 5. Both fluid lines and most electrical connections pass there. For high-current or high-voltage connections separate flanged connectors are used to not interfere with control or measurement signals. Video recordings test or diagnostic recordings can be realized through optical accesses around the vacuum chamber. Four of these windows with 250 mm in diameter are located around the first chamber section, five others around the second section. Additionally smaller flanges around the chamber can be used for other measurement equipment, pressure transducers, further piping, venting or as special interfaces (Figure 1 and Figure 4).

### 3.2.2. 2-Staged $GN_2$ Ejector-Diffusor System

With the ejector-diffusor system it is possible to achieve subatmospheric pressures during thruster hot-firings. The system consists of two stages and is driven by gaseous nitrogen ($GN_2$) with supply pressures up to 45 bar, shown in Figure 3*Figure **1***. This system ensures high-altitude conditions by effectively sucking off the thruster's exhaust gases. With both stages running more than 11 m³/s can be sucked off, correlating to approximately 250 N of thrust and a vacuum pressure below 30 mbar can be maintained solely with the ejector-diffusor unit. To drive both stages 3.5 kg/s of gaseous nitrogen are needed. For that reason a direct supply line to M11's central nitrogen storage containing 5.2 m³ at 200 bar is installed.

*Figure 3. 2-stages $GN_2$ ejector-diffusor system; 1st stage horizontal, 2nd stage vertical*

Alternatively, in cases where only reduced atmospheric pressures are needed, there is the possibility to run solely the second stage of the ejector diffusor system thereby resulting in pressures around 125 mbar. Compared to ejector-diffusor systems running on hot steam as driving fluid, the cold gas nitrogen system used at test facility M11.2 is larger in dimension and blowing gas consume. One stage of a steam-driven ejector-diffusor unit would suffice for the herein considered applications. Advantageous with the cold gas ejector-diffusor is the very short startup transient, especially when considering ignition tests or fundamental combustion tests where test duration is most often below 10 seconds. In addition with the use of pressurized nitrogen as blowing gas, there is no hazard with additional fuel or oxidizer from the vacuum generation system. Not to mention the unavoidable and complicated cooling systems for hot-gas ejector-diffusors. Otherwise safety precautions need to be increased when modifications of the experimental thruster are made or the feeding system is refueled.

### 3.2.3. Mechanical Vacuum Pumps

Aside the ejector-diffusor system mechanical vacuum pumps are used to achieve subatmospheric test environments at test facility M11.2. Especially for pre-evacuation of the chamber and maintaining subatmospheric environment during thruster preheating and cooldown phases two oil-sealed rotary pumps with volumetric flowrates of 300 m³/h each can be used. For smaller thrusters, like the tests with a 1 N $H_2O_2$ monopropellant thruster presented in section 4.3, sole operation of both vacuum pumps can suffice to keep the chamber evacuated below 3 mbar. Evacuation of fluid and propellant lines can be realized by oil-free vacuum pumps or for larger volumes with the help of a Scrollvac pump discarding 78 m³/h.

### 3.2.4. Exhaust Gas Diffusor Insert

Different exhaust gas diffusors can be installed into the vacuum chamber separator, shown in Figure 4 wall to use the thruster exhaust gases to additionally evacuate the thruster compartment. In principle this insert serves as another (half) ejector-diffusor stage running on thruster exhaust gases as blowing gas. It lowers the pressure inside the first chamber section during the thruster firing. This can be extended by equipping the M11.2 exhaust gas diffusor insert with an auxiliary nitrogen nozzle. This special element functions as complete ejector-diffusor stage evacuating the chamber when the thruster is not firing and emitting exhaust gases.

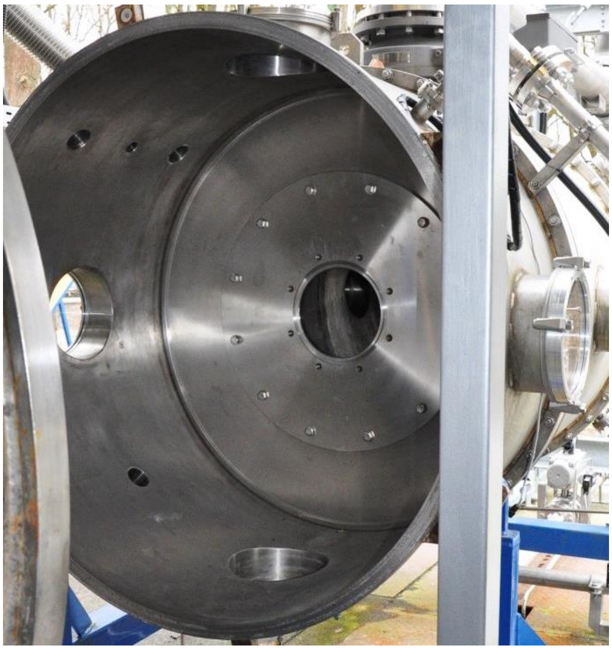

*Figure 4. Vacuum chamber with thruster compartment and separation wall without exhaust gas diffusor insert*

The inserts are adapted to the tested thrusters in respect of nozzle expansion ratio as well as used propellants and research purpose. For longer test durations the inserts should contain a cooling system. Different exhaust gas diffusor types with auxiliary blowing gas supply are possible and can be developed and tested at test facility M11.2, too.

#### 3.2.5. Vacuum Slide

At the junction of the vacuum chamber and the ejector-diffusor system a fast-closing, full-flow slide is installed. The nominal diameter of the slide is 250 mm and opening and closing times are below 1 s. Primary purpose of this slide is to avoid mechanical loads mainly onto thruster nozzles. When the ejector diffusor blowing gas is cut off, the supersonic flow inside the system collapses and repressurization shocks are initiated. Without closing the slide and sealing off the vacuum chamber these occurring shocks could damage the expansion nozzles. Especially when no exhaust gas diffusor insert is installed. Furthermore the vacuum valve is used to pre-evacuate the chamber by mechanical vacuum pumps or to keep the chamber evacuated during heat-up or cool-down phases.

### 3.3. Fluids and Gas Supply Systems

M11.2 infrastructure provides several gases and liquids to conduct the experiments. Taking into account the design philosophy of the facility without provision of propellant systems, these are described in a separate section.

The test facility is connected to the central gas storage of test complex M11 and is provided with gaseous $H_2$, $O_2$, $N_2$ and pressurized air up to 200 bar. Adjustment or regulation of the pressures is done directly at the test position. While hydrogen and oxygen are mainly used to run torch igniters, nitrogen is used for multiple purposes. First it is used to operate servo-actuated valves and slides at the test facility, seen for example in Figure 5. Second, it is used for flushing or cooling of experimental combustion chambers. Third, it is used to vent or regulate the pressure inside the vacuum chamber when air cannot be used and fourth, it is used as pressuring gas for cooling and tap water as well as for the propellant systems in most of the cases.

Aside the propellants temperature regulated water is used for exhaust gas cooling inside the vacuum chamber. Furthermore deionized water can be used as well as tap water; for flushing operations or cooling of research combustion chambers.

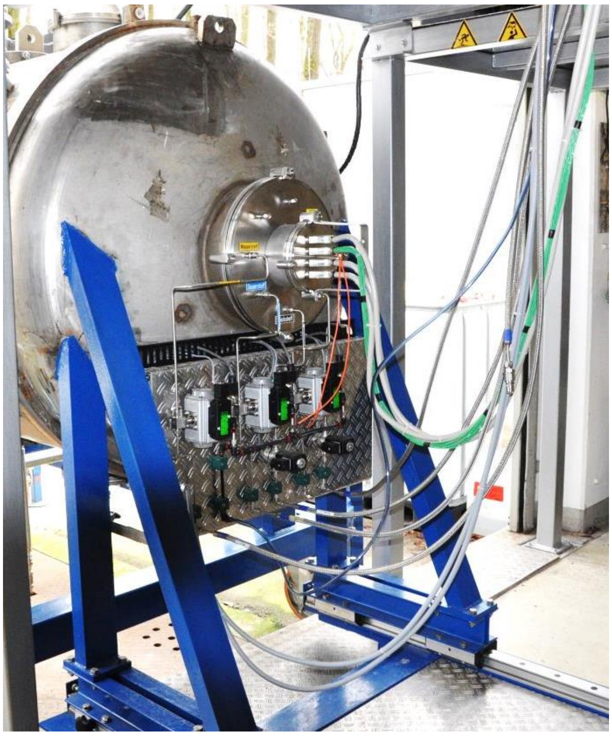

*Figure 5. Closed rail-based vacuum chamber lid with electrical interfaces and fluid lines and valves*

### 3.4. Propellant Systems

The feeding system is a relevant part for the conduction of thruster and combustion tests. A special feature with M11.2 is the high flexibility with the propellant systems. Usually a test bench is specially designed for one propellant or propellant combination. In contrast, M11.2 is designed in a way that a multitude of propellants and feeding systems can be tested.

Conventional orbital or satellite propulsion systems operate in blow down or pressure regulated modes. Therefore, M11.2 provides two separate pressure regulated ports at which the thruster feeding system or research propellant tanks can be attached. Both ports are completely PID controlled. Constant feeding pressures, blow-down modes or pressure ramps can be realized and adjusted during test campaigns. For most of the conducted tests using nitrogen as pressurizing gas is sufficient. If required, switching to helium is possible as well.

This system design allows an excellent adaption of the feeding systems to the selected propellants and mass flows, ranging from 1 N blow-down monopropellant system to a 200 N hypergolic pressure-regulated system.

### 3.5. Electrical Supply System

The electrical supply system is important to operate valves, actuators, regulators and to activate heaters of the test bench, the feeding system and the thruster. The major part of the test bench, especially all valves and regulators operate on 24 V DC. Moreover, 220 V AC are used for some power demanding operations like the high voltage supply for spark plugs. Additionally, a 12 V or a 5 V DC are supplied and can be used. Other voltages can be realized by DC power-supply units. Some of these units can either be manually adjusted, e.g. 28 V for flight-like FCV, or software controlled, e.g. for heater units or glow plugs.

### 3.6. Measurement and Control System

The measurement and control system is another key part of the test facility. Main component is a Jäger real-time measurement and control system. The control system includes 48 transistor output channels to operate valves and actuators. 25 of them are reserved for fixed test facility hardware, whilst the rest can be unrestrictedly used for propellant feeding system, triggering or other mobile setups. Aside the transistor outputs there are 8 analog voltage outputs ranging from -10 to 10 V as well. These can for example be used to regulate PID controllers or DC power-supply units.

The measurement equipment incorporates 64 analog input channels, of which 32 are connected to Dewetron amplifiers. Additionally, 32 thermocouple channels are recorded. To preserve flexibility thermocouples and analog channels can be used both inside as well as outside the vacuum chamber depending on the requirements of the experimental setup.

While the main control actuators, e.g. main valves, are permanently installed and programmed in the software, the experimental setup consisting of propellant systems and experimental combustion chamber is mounted, plugged and then included in the software. Besides the real-time system a Labview-based program is used to control and visualize the parameters. Test sequences and emergency redlines can then be chosen from predefined ones, newly programmed or modified depending on the requirements and research goals.

## 4. Research Activities

In this section an overview of conducted tests at M11.2 shall be given and the flexibility of the test facility shall be shown.

### 4.1. ADN-based Propellants

DLR participated in the RHEFORM project [7, 8] that was conducted from 2015 till the end of 2017. One of the main goals was to enhance hydrazine replacements based on aqueous ADN-containing monopropellants in terms ignitability. All thermal ignition pretests and tests as well as the final catalytic thruster tests were conducted at DLR's test facility M11.2. The thermal ignition development was done for a 200 N (Figure **6**) thruster while catalytic ignition was carried out for a 20 N thruster (Figure **7**) by project partners. The propellant system for the ignition tests was kept relatively simple for monopropellants. The system consisted of a 2 l stainless steel tank and stainless steel tubing including a flow measurement turbine, pressure transducers and thermocouples. The ignition demonstrator also equipped with pressure transducers and thermocouples and a rail-based thrust balance was used. Besides the propellant line, connections for nitrogen and water flushing of the combustion chamber were installed and operated via 24 V DC valves.

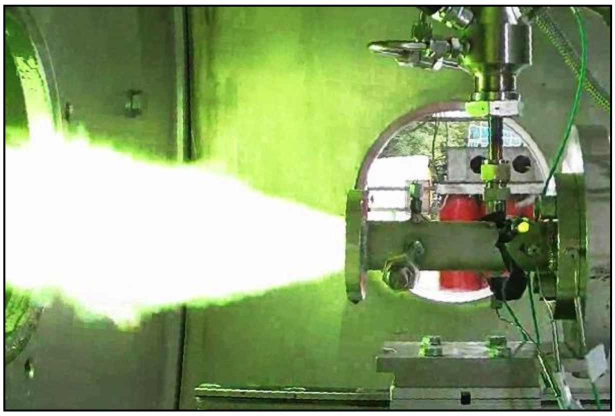

*Figure 6. Thermal ignition demonstrator used in the RHEFORM project [8]*

The experimental catalytic thruster was higher in TRL and the FCV was operated on 28 V while the catalyst heater was supplied with variable voltage to regulate preheating temperatures. Furthermore, it was installed in a water-cooled thrust balance using a piezoelectric force sensor. Due to the lower thrust class propellant mass flows were smaller and the propellant system was modified with a scale to measure the consumed propellant mass during pulse-mode firings.

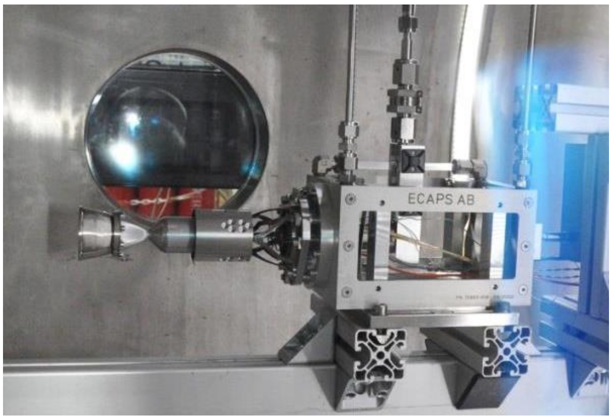


*Figure 7. Experimental 20 N thruster from ECAPS used during catalyst development in the RHEFORM project*

### 4.2. Flashing of Multicomponent Mixtures [4]

Furthermore, research is conducted on flashing and de-mixing phenomena of multicomponent liquid mixtures [9]. This is an important topic for hydrazine replacements based on ADN. Cavitation and segregation inside a satellite's feeding system or injector can influence the propulsion system performance or lead to clogged feeding lines, valves or injectors and influences spray and ignition behaviour as well.

The test setup for a laser-based determination of segregation effects is shown in Figure 8. Instead of the M11.2 vacuum chamber as separate vacuum tank was used for these tests. The vacuum generation was done using the mechanical pumps of the facility. The propellant system consisted of a 5 l stainless steel tank that was connected to the PID-controlled nitrogen pressurization system. Valves for propellant, water flushing, a circulation pump and camera triggers from the mobile setup were implemented at M11.2. Furthermore, a tank temperature regulation system as well as a laser control setup was programmed into the M11.2 control software. Measurement equipment included thermocouples, pressure sensors, a coriolis mass flow meter and high speed cameras.

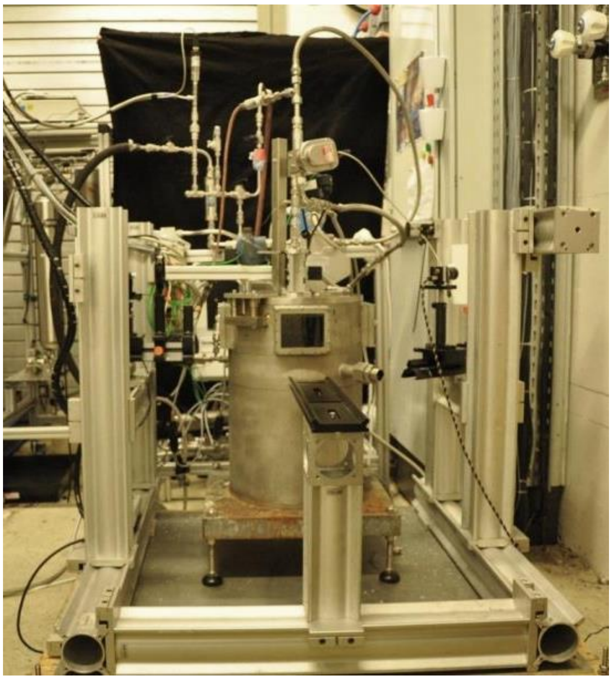

*Figure 8. Setup for laser-based quantification of segregation effects with salt based propellant mixtures*

### 4.3. $H_2O_2$-Based Propellants Fundamental Research [10]

At test complex M11 $H_2O_2$-based propellants are investigated as green hydrazine replacements for launcher and orbital propulsion systems. Test facility M11.2 was used for an investigation of catalytic $H_2O_2$-monopropellants in cooperation with Ariane Group.

The setup consisted of a flight like 1 N thruster with a cartridge heater and a flight valve both using 28 V DC. The thruster installed on the baseframe at M11.2 is shown in Figure 10. The corresponding propellant system, as can be seen in Figure 9, was set up of a passivated propellant tank and tubings including a Coriolis mass flow meter and control valves for fueling, defueling and venting. Additionally, high purity water was provided for flushing operations and nitrogen inside the vacuum chamber to temper the thruster after hot firings.

*Figure 9. Propellant system used for high concentrated $H_2O_2$ monopropellant tests*

Auxiliary to the coriolis a weight scale was installed to measure the integrated propellant consume, especially during pulse mode operations. Vacuum generation in during pulse and steady-state firings was realized by operation of the mechanical vacuum pumps.

Measurement equipment used during these tests consisted of pressure transducers and thermocouples, mass flow and mass measurements as well as video recordings.

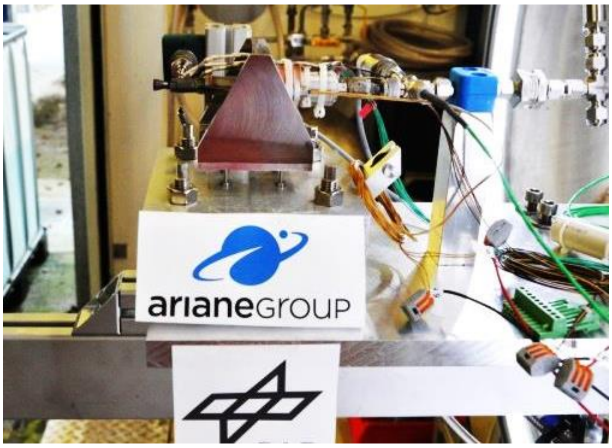


*Figure 10. Experimental 1 N $H_2O_2$ thruster test-ready mounted on the vacuum chamber lid*

## 5. Future Activities

Research on hydrazine replacements for satellite and orbital propulsion systems will continue at test facility M11.2. Propellants based on ADN and $H_2O_2$ will be further investigated with regard to ignition behavior and performance. Moreover, research will be extended to bipropellants and hypergols based on both components and as well on energetic ionic liquids. In addition, first subatmospheric testing of a HyNOx-thruster is planned. The experimental HyNOx-thruster combusts nitrous oxide and hydrocarbons.

## ACKNOWLEDGEMENTS

The authors would like to thank the M11 team, Mr. L. Werling, Mr. I. Dörr, Mr. H. Friedrich and Mr. J. Buddenberg, for their outstanding support during construction, installation and initial operation of the test facility M11.2. Furthermore we would like to express our gratitude to the Engineering Department of the Institute of Space Propulsion for designing the vacuum generation system.

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