Progress report regarding hybrid propulsion rocket development at WARR

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Abstract

The *Wissenschaftliche Arbeitsgemeinschaft für Raketentechnik und Raumfahrt*[1] (WARR) is a student group at Technische Universität München (TUM). Taking part in the STERN initiative, proposed by the *German Aerospace Center* (DLR), the WARR group can build on its experiences obtained during the WARR-Ex2 project, which yielded an experimental single-staged sounding rocket and the associated hybrid rocket motor HYPER1. The latest full duration test of the engine will be presented and discussed, as it demonstrates the current status of WARR's hybrid propulsion technology. Using the experiences of this earlier project, a first study of the future rocket engine for WARR's implementation of the STERN program has been created during project phase 0. By now, WARR's STERN project has reached early project phase A, meaning that top level requirements and basic system architecture have been defined. Following the results of the STERN engine's design study, the current project status will be presented.

1. Introduction

The WARR group has a long tradition of hybrid propulsion rocket motors: Founded by Prof. Robert Schmucker in 1962, the WARR has constructed and launched the first hybrid propelled rocket *Barbarella* to fly in Germany in 1974. Since then, WARR has been working in many space related fields, such as hybrid and liquid propulsion, interstellar space flight and the space elevator. In 2012 the WARR has been extended with a satellite-technology group, constructing a cube-sat. Since 2013 the WARR started a cooperation with the Institute for Flight Propulsion at TUM, to participate in the *Studentische Experimental Raketen* (STERN, engl.: Student Experimental Rockets) program of the *Deutsches Zentrum für Luft- und Raumfahrt* (DLR, engl.: Germany Aerospace Center).

Being part of the technological origin of the new STERN project, WARR's 10 000 N s hybrid rocket engine HYPER1 has successfully been used on the test bench since early 2012. Results of the first tests and simulations have been published at the IAC 2012 [12]. In March 2013 first tests with a pressurized oxidizer tank have been performed. As a result, a constant combustion chamber pressure has been achieved. The test-setup and results are presented in chapter 2. Based on past experiences, WARR's contribution to the STERN project contains a completely new hybrid motor. During project phase 0, an early design for the planned rocket engine has been created. Using parameter study, an optimum configuration for the given requirements has been determined and is presented in section 3. Since the project start in March 2013, the project has reached early phase A. Thus a basic system architecture as well as the future development is be presented in section 4.

2. HYPER1 validation test

As announced in [12], WARR has conducted the first full duration test of the HYPER1 rocket motor in early 2013. The test aimed at verifying the performance requirements of a 10 s operation, while delivering an average thrust of 1000 N. For further examination of the motor's operational behavior, an oxidizer-pressurization system has been established. The ability to provide a constant combustion chamber pressure and oxidizer mass flow has been part of the test's objectives. This steady state condition is needed to determine the time-averaged regression rate of the solid fuel.

[1] engl. Scientific Workgroup for Rocketry and Spaceflight

2.1 Test setup

The following section describes the setup of the test, including a brief description of the test-bench and the used fuel (HTPB). The test-bench consists of two elements: The motor-test-bench itself holds the combustion chamber and oxidizer main valve. The chamber is mounted on flat springs, so thrust can be measured using a load cell (see figure 1). The motor-test-bench is connected to the oxidizer supply via the main oxidizer feed line.

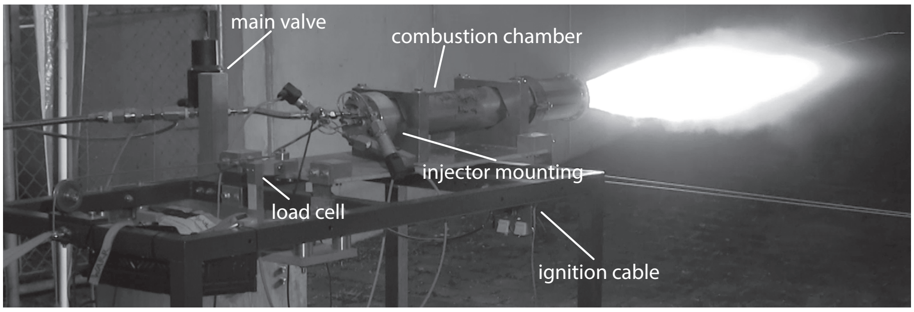


Figure 1: Snapshot from HYPER1 test video record

2.1.1 Oxidizer supply

The oxidizer supply consists of a high pressure tank for the nitrous oxide (N_2O) and a standard 10 L nitrogen gas cylinder for pressurization. Both are mounted movable, to measure the combined mass of oxidizer and pressurization gas. Thus only the mass flow from the tank to the combustion chamber is measured. Figure 2 shows a simplified fluid plan of the test bench, including the positions of pressure-measurements.

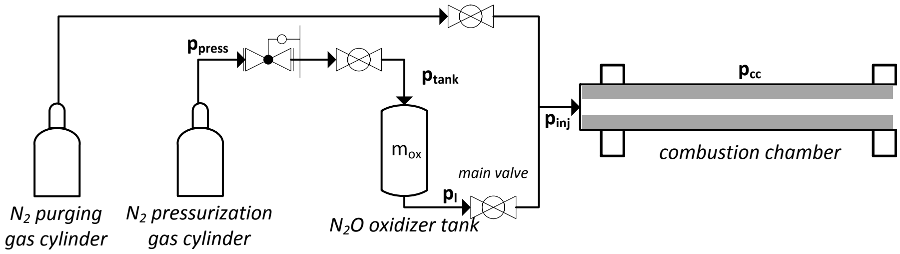


Figure 2: Simplified fluid plan of the test setup

The oxidizer tank, providing an available fluid volume of $V_{tank} = 7570\,\text{cm}^3$, is filled with $m_{ox,0} = 5.82\,\text{kg}$ nitrous oxide. As the oxidizer is fed into the tank from a standard gas cylinder at saturation conditions, the oxidizer tank contains a mixture of liquid nitrous oxide on the bottom and vapor phase on the top. Assuming an oxidizer temperature of 5 °C and using the saturation properties for N_2O the vapor mass fraction x in the tank can be calculated from:

$$m_{ox,0} \cdot \left(\frac{x}{\rho_{N_2O,v}} + \frac{1-x}{\rho_{N_2O,l}} \right) = V_{tank} \tag{1}$$

This leads to a liquid mass of $m_{ox,l,0} = 5.716\,\text{kg}$ and $m_{ox,v,0} = 0.104\,\text{kg}$ of gas phase. During test preparation the feed line between pressurization gas and the oxidizer tank is opened via a pressure controller. The oxidizer tank pressure is adjusted to $p_{tank} = 60\,\text{bar}$, which reduces the pressure in the nitrogen cylinder to $p_{press} = 170\,\text{bar}$.

2.1.2 Grain and igniter

The HYPER1 rocket motor uses a HTPB solid fuel block with a nominal size of 550 mm × 73.5 mm and an initial inner diameter of 45 mm. Several formulations have been tested during production of the grains, leading to the currently used formulation (see table 1), which was primarily selected for its mechanical properties and operability.

The HTPB is cast into a FR-2[2] liner which provides thermal insulation to the combustion chamber and mechanical stability. The grain used in the presented test had an initial mass of $m_{fuel,0} = 1.851\,\text{kg}$, including the liner. The

[2] *Flame Resistant 2*: paper impregnated with a plasticized phenol formaldehyde resin, usually used for PCBs

Table 1: HYPER1 solid fuel formulation

Substance	Mass fraction [%]
HTPB prepolymer*	90.626
IPDI	7.771
FeAA	0.015
carbon black	1.478

* HTPB prepolymer formulation is unknown, but influences the results

igniter consists of a glow wire, coated with a $Mg/KNO_3/Epoxy$ mixture, which is glued to the injector-sided end of the grain. The ignition is initiated by the 24 V, 10 A test bench power supply.

2.1.3 Control sequence

The test has been conducted using the control sequence shown in figure 3. The ingiter forerun time of 2.5 s is empirically gained from previous motor tests. It ensures a reliable and almost instant ignition of the motor when the oxidizer is fed. After the 12 s oxidizer feed, the combustion chamber is purged with nitrogen to extinguish the grain and flush combustion products from the testing area.

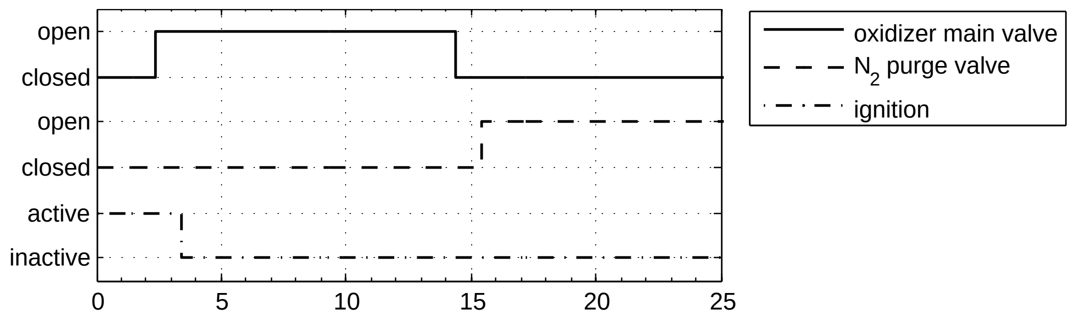


Figure 3: Valve and ignition control sequence

2.2 Result discussion

2.2.1 Oxidizer supply

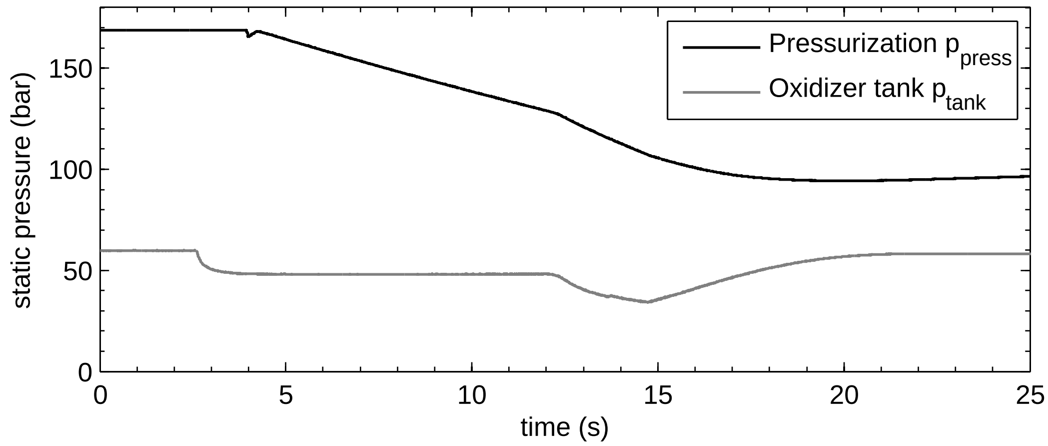
Analyzing the pressure curves in figure 4(a), five different time domains can be identified to describe the supply system's dynamic:

- 2.5 s $\leq t <$ 4 s: After opening the main oxidizer valve, it takes the pressure regulator about 1.5 s to adjust a constant tank pressure. The oxidizer mass curve (see figure 4(c)) shows the impulse response of the oxidizer supply mounting to the forces imposed by opening the main valve. The supply mounting can be regarded as a mass-spring-damper system oscillating at about 9 Hz. For future operations the system's damping shall be increased by an additional damper below the load-cell.

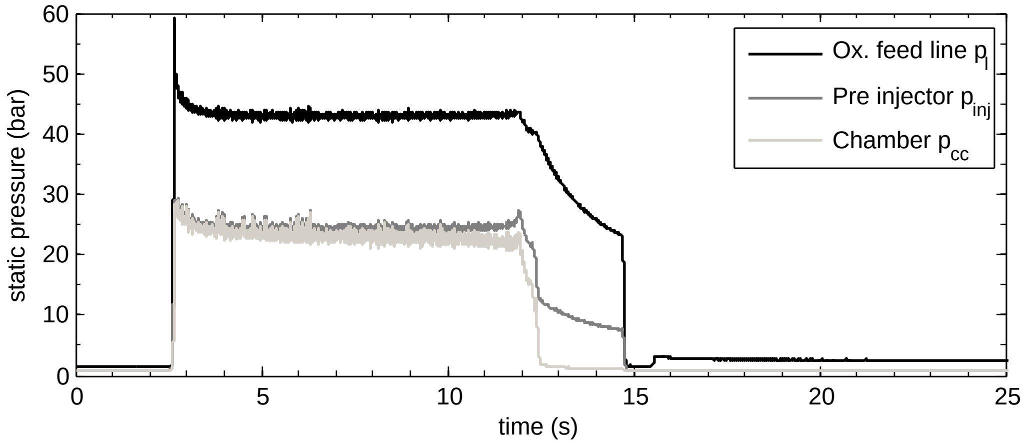
- 4 s $\leq t <$ 12.2 s: The pressurization system has reached steady state operation and feeds the 5.716 kg of liquid nitrous oxide into the combustion chamber. The pressure developments shown in fig. 4(a) and 4(b) confirm this observation. As seen in figure 4(b), the pressure drop over the injector weakens the transmission of oscillations from the combustion chamber into the fluid feed system: The combustion chamber pressure p_{cc} oscillates around 23.2 bar with an amplitude of 2.5 bar, while the injector-pressure's (p_{inj}) oscillation amplitude is reduced to 1.4 bar.

- 12.2 s $\leq t <$ 14.5 s: All available liquid N_2O has been depleted from the tank. The resulting breakdown of oxidizer mass flow (fig. 4(c)) results in a motor shut off (see fig. 4(b)). As the feed line empties with liquid phase, the pressure regulator isn't able to provide enough nitrogen-mass-flow to maintain the desired tank pressure.

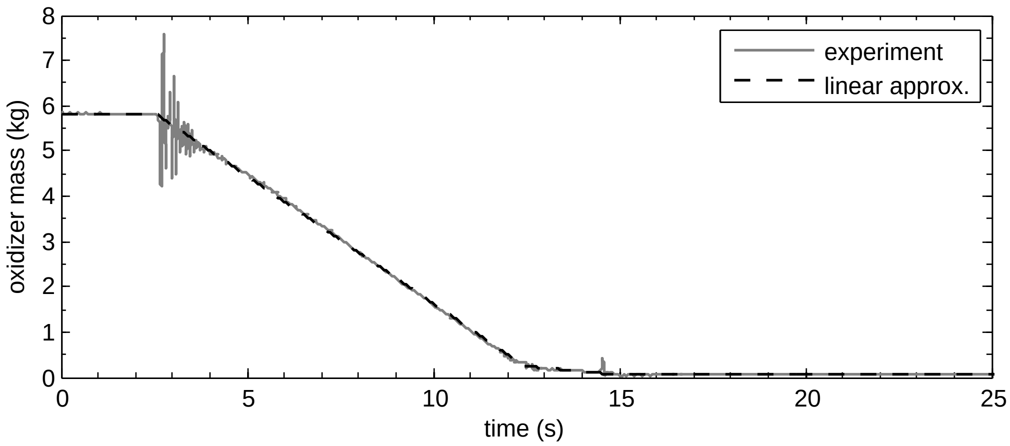
- 14.5 s $\leq t \leq$ 25 s: At t = 14.5 s the main valve closes. As the pressurization valve is still open, the tank pressure raises to the initially desired value. The automatic purging sequence leads to a slight pressure step at t = 15.5 s.



(a) Development of oxidizer supply pressures over time



(b) Development of chamber, injector and feed line pressures over time



(c) Oxidizer supply mass development over time compared to linear approximation

Figure 4: HYPER1 test results

2.2.2 Performance

As shown in figure 5 the motor produces an almost constant thrust level, which is a direct result of the mass flow rate achieved by a constant feed pressure. The rocket motor has an action time of $t_a = 9.8\,\mathrm{s}$. Integrating thrust over time, shows a resulting total impulse of $I_{tot} = 10\,550\,\mathrm{N\,s}$, which is equivalent to an average thrust of $\bar{F} = 1076.5\,\mathrm{N}$. As shown in table 2 all performance goals of the HYPER1 rocket motor have been met.

Table 2: Comparison of HYPER1 test results and design parameters

Parameter	**Design**[10]	**Test**	
Total impulse I_{tot}	10000.0	10549.8	N s
Average thrust $\bar{F}$	1000.0	1076.5	N
Average chamber pressure $\bar{p}_{cc}$	20.0	23.2	bar
Oxidizer mass flow rate $\dot{m}_{ox}$	450.0	557.2	$\mathrm{g\,s^{-1}}$
Average fuel mass flow $\bar{\dot{m}}_{HTPB}$	90.0	76.4	$\mathrm{g\,s^{-1}}$
Average O/F ratio	5.0	7.2	–
Average burning rate $\dot{r}$	1.0	0.9	$\mathrm{mm\,s^{-1}}$
Action time t_a	10.0	9.8	s

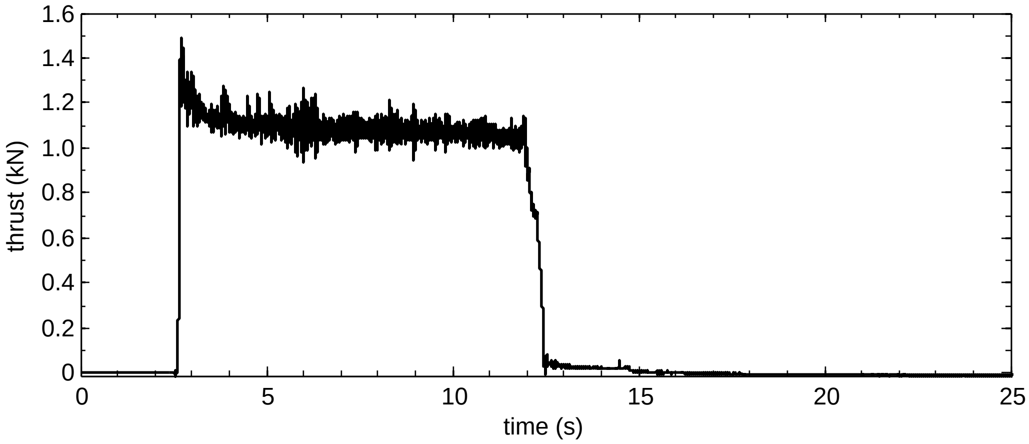


Figure 5: Development of thrust over time

The high O/F ratio is the result of the injector design used for this test, as it is optimized for blow down mode operations. This may be solved by either lowering the tank pressure or an alternative injector design. An injector providing a higher pressure drop should be preferred as it increases oscillation-decoupling between combustion chamber and oxidizer feed system.

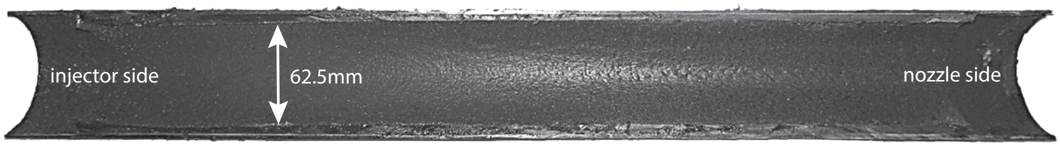


Figure 6: Opened HYPER1 grain after test

The average fuel mass flow and burning rate are calculated using before- and after-test values of the grain's mass respectively inner diameter (see figure 6).

2.2.3 Nozzle

The increased operating-time of the rocket motor results in a higher heat input into the graphite nozzle. In contrast to the previous 5 s tests, video recordings show a bright red glowing nozzle, right after motor shut-down. Comparison with annealing color tables [6] indicates a surface temperature of 900 °C to 1100 °C. Though solid particles were seen in the exhaust jet no major damage to the motor, except for a slight roughening of the nozzle's throat has been found. The visible sparks are assumed to be parts of the igniter and burned liner material.

3. Preliminary design of the STERN-motor

As part of WARR's STERN project a rocket is designed to be propelled by a hybrid-rocket-motor developed by WARR. For obtaining the principal motor characteristics, a preliminary design study concerning the basic motor parameters is conducted ([2]). Since the motor is a primary design driver in the rocket's design by determining the majority of the system's specifications, a rough dimensioning of all involved subsystems is undertaken. Approximate values of the flight characteristics, i.e. ceiling, acceleration during lift off and maximum Mach number achieved during flight are calculated. Based on the obtained results a maximization of ceiling in compliance with the minimum start acceleration, necessary to obtain stable flight conditions, is conducted. The following optimization parameters are examined:

- the grain cross-sectional geometry
- the nozzle expansion ratio ϵ
- the nozzle throat area A_{th}
- the injection characteristics c_{inj}
- the chamber pressure p_c
- the pre-injection pressure p_{inj}

The dynamic combustion chamber behavior is modeled using an ideal gas approach and assuming constant substance properties across the chamber as well as quasi steady-state conditions and chemical equilibrium. The injection process is modeled according to [11]:

$$\dot{m}_{inj} = c_{inj} \cdot \left(p_{inj} - p_c\right)^{0.5} \tag{2}$$

where $\dot{m}_{inj}$ denotes the injected oxidizer mass-flow and c_{inj} represents a constant, describing the characteristic of the injector. The total mass-flow leaving the combustion-chamber is obtained by

$$\dot{m}_{out} = \frac{p_c \cdot A_{th}}{c^*} \tag{3}$$

with $\dot{m}_{out}$ being the exhaust mass flow rate and c^* the characteristic velocity calculated with the CEA-code [7].
The regression rate inside the solid fuel grain is calculated using the regression-law according to Marxman and Gilbert [3]. For a uniform Prandtl number, without compressibility corrections and disregarding heat transfer from radiation this yields:

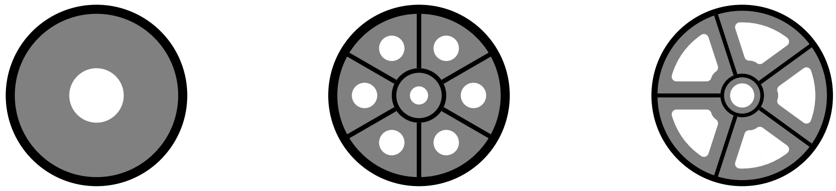
$$\frac{\partial r}{\partial t} = \frac{0.03 \cdot \eta^{0.2}}{\rho_f} \cdot G^{0.8} \cdot B \cdot \frac{St}{St_0} \cdot x^{-0.2} \tag{4}$$

Here r is the distance the solid fuel surface has regressed up to the current timestep, η is the dynamic viscosity of the flow, ρ_f the solid fuel density, G the total mass flux at position x, B the blowing parameter characterizing the effect of the fuel mass flow evolving from the regressing surface, $\frac{St}{St_0}$ the ratio of the Stanton numbers with and without surface mass-flow and x the distance from the grain's front edge. From the regression rate the mass-flow is calculated using

$$d\dot{m}_f = \rho_f \cdot \frac{\partial r}{\partial x} \cdot l_p \cdot dx \tag{5}$$

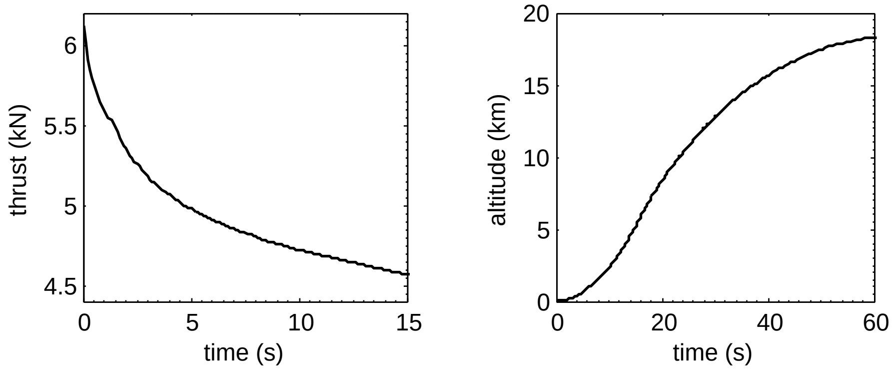
where l_p denotes the mass flow producing perimeter of the grain's cross-section.

Due to the rocket's flight performance requirements, a cylindrical single-port-geometry, as used in the earlier hybrid rocket motors built, is not appropriate. Mass flux is approximately proportional to the perimeter and the inverse cross-sectional area. In order to generate high thrust within a limited motor size, a high perimeter combined with a small area should be targeted when choosing the port geometry. This can be achieved by using multiple ports. Due to the liner structure required for ensuring the integrity of multi-port geometry grains, not the entire fuel mass can be burned efficiently. The wagon wheel geometry holds less residual fuel at burnout than a cylindrical multi-port (cf. figure 7). The corresponding geometry has been optimized by a parametric study. An optimum can be found for a nine plus one configuration, whereat the segment number has been limited to ensure feasibility of manufacturing and ignition. The flight altitude and thrust curve of the optimized configuration are shown in figure 8.



(a) Cylindrical singleport (b) Cylindrical multiport (c) Wagon wheel

Figure 7: Solid fuel grain geometries



(a) Development of thrust over time (b) Development of flight altitude over time

Figure 8: Characteristics of optimized configuration

4. Future development for STERN

The STERN program of the DLR enables aerospace engineering students at higher education to "develop, build and launch theirs own rockets" [9]. Funding is provided to participating universities by the *Bundesministerium für Wirtschaft und Technologie* (BMWi, engl.: Federal Ministry of Economics and Technology) for three years. As STERN being an educational DLR program, the focus is on running the students through the project life cycle of a space project and gaining overall system competence by developing an entire rocket launch system.

Traditionally, projects at the WARR have been funded by tuition fees and material sponsoring from industry partners. Long-term planning and thus larger projects have hardly been possible. By providing founding from March 2013 on for the duration of three years to the *Lehrstuhl für Flugantriebe* (LFA, engl.: Institute for Flight Propulsion) at the TUM, the STERN program enables the development of a new rocket system by the WARR in cooperation with the LFA; WARR's most advanced rocket system by means of mission parameters and high-energy propellants. The mission statement of WARR's STERN project reads similar to the one of the STERN program [9]: "Launch a rocket, developed by the WARR, using LOX and HTPB as propellants, at the Swedish ESRANGE Space Center until spring 2016." The WARR's primary objectives in the STERN program are:

- Performing supersonic rocket flight.
- Breaking the current height record of amateur rockets in Europe at 12.55 km altitude [9].
- Launching in spring 2016 at the ESRANGE Space Center.
- Using LOX and HTPB as propellant for the rocket motor.

The constraint of only using LOX and HTPB as propellants traces from the WARR's need to provide students the opportunity of gaining experience on space industry standards, like utilizing and handling of cryogenic propellants, and the programmatic decision to use the already existent knowledge at WARR of using HTPB as propellant in hybrid rocket motors.
The Mission profile is typical for a sounding rocket: It includes pre-launch preparations, launch, flight, parachute operation and recovery. This mission together with stakeholder objectives translate into the following technical top-level requirements and constraints, which comply to the objectives of the STERN program, the LFA and the WARR:

- The rocket shall reach apogee at minimum 15 km altitude.
- The rocket shall reach a Mach number of minimum 1.4 Ma.
- The rocket shall provide acceleration, velocity and height data via telemetry during flight.
- The rocket shall use a hybrid rocket motor with LOX and HTPB as propellants.
- The rocket shall be launched at ESRANGE Space Center.
- The rocket launch system shall comply with the ESRANGE safety regulations.
- All parts of the rocket shall be recovered after flight.
- The System shall prevent damage to persons.

4.1 Project status and organization

At time of issue, the WARR STERN project is in early phase A [5], where development of the system architecture, technical concepts and capturing requirements characterize the work packages. After phase 0, the mission is defined and the project team is recruited. The project team consists of former members of the WARR, experienced in development and deployment of hybrid rocket engines, and new members form different semesters and faculties at the TUM. The team counts 38 members in total. A flat organization hierarchy has been implemented, with teams evolving with the project phases and the team leaders making up the project management team.

4.2 General system overview

The rocket launch system to be developed by the WARR during its STERN program participation is divided into a flight segment and a ground segment. The flight system consists of the rocket and all of its subsystems. Development and launch of the rocket is a primary objective, hence the rocket it not used for any transport purposes and the only payload is the telemetry system. The ground segment contains a launch-platform (launcher), launch-control, a tracking/telemetry system and a supply infrastructure for LOX, electric power and pressure gases.

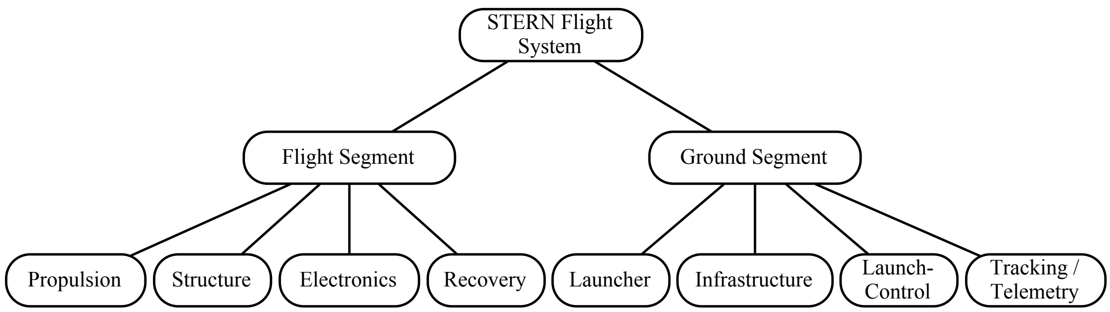


Figure 9: WARR's STERN flight system overview

4.3 Preliminary system configuration

The flight segment's propulsion system composes of a hybrid rocket motor and the correlating fluid system. The motor is projected to deliver 4.9 kN of thrust for 15.3 s as calculated in 3 [2]. The rocket motor is using LOX and HTPB as propellants. The solid grain's geometry is proposed as a wagon-wheel. The Nozzle is passively cooled. The injector concept has yet to be determined. The fluid system consists of a LOX tank, a N_2 tank for a LOX pressurization system as well as vents for LOX fueling, motor supply and pressurization. Electronics is divided into two different systems: Recovery and 'Telemetry and Instrumentation'. The Recovery System contains a single parachute deployed in two stages by a reefing system after shaft separation of the rocket. The rocket is passively stabilized by the aerodynamic design of the structure, which consists of a nosecone, body and fins.

The ground segment's launcher is the interface between the rocket, supply infrastructure and Launch-Control and it provides guidance to the rocket during the lift-off phase. Since the rocket is unguided, the azimuth and heading configuration of the launcher is critical for safe launch operations and needs to be adjusted to the launch environment. Functions of Launch-Control are control and monitoring of the remote fueling of the rocket on the launcher and ignition. Maintenance data and control feedback for pre-launch operations and information for the 'GO for launch' decision is also provided by Launch-Control. The Tracking/Telemetry System receives telemetry of the rocket during flight.

4.4 Critical technology development

The development and deployment of hybrid rocket engines at the WARR can be rated at Technological Readiness Level (TRL) [8] 6 as multiple engines have been developed and deployed successfully on the test-bench during the last 3 years [4]. Many technologies needed for the STERN project of WARR are ready to use: I.e. the Reefing System enabling a two-stage deployment of the main parachute has been developed for the WARR-Ex2 rocket, is flight verified on the WARR-Ex1 rocket and thus is to be rated TRL 7. Analysis of the early STERN design at the WARR leads also to a number of critical technologies that need to be newly developed during the WARR's STERN project:

1. A preliminary analysis of the required rocket motor design for WARR's STERN project has been carried out in the bachelor's thesis of Alexander Chemnitz [2]. The analysis shows, that it is possible to design a hybrid rocket motor with the performance required to fulfill the WARR STERN project objectives.
   (a) A wagon-wheel design of the grain geometry is proposed for optimal performance. Manufacturing of cylindrical HTPB grains at the WARR is at TRL 6, being successfully used at tests (see section 2) for over one year. Technologies for manufacturing more complex grain geometries of HTPB are to be developed and are at TRL 2.
   (b) Ignition of a multiple-port LOX hybrid rocket is rated as TRL 0 as no experience exists at the WARR.
   (c) Injection of LOX in a rocket motor burning chamber is to be rated TRL 0 as well for the same reason.
2. The cryogenic infrastructure on the rocket's fluid system, at the ground segment and at the test-bed is at TRL 2 by the experience of chair employees and is assessed in a bachelor's thesis on the design of an oxygen liquifier [1].
3. The interface of flight- and ground segment for supplying the rocket with oxidizer, power and signals on the launcher is TRL 4 as a similar system is in development for the launcher of WARR's WARR-Ex2 rocket.

4.5 Testing

Rocket motor tests during WARR's STERN project shall take place at the test facilities of the LFA at the TUM. Therefore a cryogenic test infrastructure has to be established at the test site in cooperation with the LFA. This infrastructure will add to the existing test facilities for hybrid and liquid rocket engines at WARR's test field. WARR is going to make use of the infrastructure for component- and sub scale testing during phase B (LOX Injector, LOX Igniter) as well as for full scale testing during phase C and qualification of the flight motor in phase D.

5. Conclusion

The successful test of the HYPER1 motor and the verification of its performance requirements confirm the ability of WARR to develop and operate hybrid rocket motors. The HYPER1 engine will be used on the WARR-Ex2 experimental rocket, demonstrating in-flight functionality. The gathered experiences enable WARR to reach for a new technological level in terms of the STERN motor's performance characteristics and utilization of cryogenic fluids. Products of the WARR-Ex2 project will be further used in the STERN project. I.e. the WARR Ex-2 rocket will be used for flight-qulification of STERN subsystems and the existing hybrid rocket engine test-bench will be used for subscale testing of the STERN engine.

Up to now a preliminary design study has been performed, providing a base for further system development. Long-lead items have started with the construction of an oxygen liquifier and the cryogenic test-bench infrastructure. A project team has been set up working on phase A, which will conclude midterm 2013 with an internal Preliminary Requirements Review (PRR) [5]. Following phase B, the Preliminary Design Review (PDR) with DLR MORABA is planned for December 2013.

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