# Gelled Rocket Propellants – Development and Performance

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## Abstract

Key advantages of Gelled Propellant Rocket Motors GRM and Gelled Propellant Gas Generators (GGG) are highly controllable thrust and very low hazard potential. Currently, Bayern-Chemie´s operates monopropellant GRM / GGG systems with very stable combustion, very fast and smooth thrust control and a high degree of environmentally friendliness. After a short introduction, the paper describes the method and results of propellant development. The family of monopropellants with different fuel blends, gelling agents, additives and particles have excellent manufacturing, handling, transport and storage properties and can be adapted to widely differing applications. The outlook sketches the further directions of development.

## Nomenclature

### Parameters

| | | |
|---|---|---|
| $A$ | [m$^2$] | Area |
| $F$ | [N] | Force, Thrust |
| $I_{spec}$, $I_{sp}$ | [m/s] | Specific impulse |
| $I_{spec,vol}$ | [N*s/m$^3$] | Volumetric specific impulse |
| $p$ | [Pa] | Pressure |
| $T$ | [K] | Temperature |
| $V$ | [m$^3$] | Volume |
| $x$ | [m] | Displacement in $x$-direction |
| $\rho$ | [kg/m$^3$] | Density |

### Subscipts

| | |
|---|---|
| c | Combustion |
| CC | Combustion chamber |
| GG | Gas generator |
| GRP | Gelled rocket propellant |
| min | Minimum value |
| ∞ | Ambient condition |

### Abbreviations

| | |
|---|---|
| ACS | Attitude control system |
| CC | Combustion chamber |
| DACS | Divert and attitude control system |
| GG | Gas generator |
| GGG | Gelled propellant gas generator |
| GP | Gelled propellant |
| FMFR | Fuel mass flow rate |
| GRM | Gelled propellant rocket motor |
| GRP | Gelled rocket propellant |
| IRFNA | Inhibited red fuming nitric acid |
| MMH | Monomethylhydrazine |
| MON | Miyed oxides of nitrogen |
| NTO | $N_2O_4$ |
| UDMH | Unsymmetrical dimethylhydrazine |

## 1. Introduction

Established in the year 2001 by the German MoD, Bayern-Chemie and national institutes, the national gel propellant team {Bayern-Chemie, Fraunhofer Institut für Chemische Technologie (ICT) & Deutsches Luft- und Raumfahrtzentrum (DLR)} started to develop the technology needed to build a rocket motor burning gelled propellants [1 - 4]. The primary goal for the development of the Gelled Propellant Rocket Motor (GRM) was to realize a throttleable rocket motor that has a very high degree of insensitivity. This is achieved because the gelled propellant (GP) is essentially solid in the tank and liquefies upon injection into the combustion chamber due to the high shear rates. References [5, 6] give detailed information on DLR´s activities on rheology, spraying and combustion behaviour of GP. Gelled propellants are by nature less critical than liquids, because

- The gel does not spill out of the tank in case of a leakage or perforation
- The evaporation surface of gelled propellant that has been set free is very small because the gel does not produce wide leaches
- The evaporation rate of the gelled propellant is much smaller than that of the liquid
- The gel does not soak into the soil or flows into sewers which makes clean-up operations after accidents much easier than for accidents with liquids.

Alltogether, a liquid that readily produces intensive fire, is hardly flammable in gelled state. This significantly reduces the hazard of a GRM in case of an accident, compared with any other kind of rocket motor, should it use solid or liquid fuel.

Other benefits of GP are:

- Fine particles can be suspended in the gelled propellant without the risk of sedimentation over time. This allows to increase the energy, i. e. the specific impulse and the propellant density
- GP produce no sloshing in the tanks.

The same properties have gas generators (GG) that burn gelled propellant (GGG)

The GRM / GGG at BC is currently a monopropellant system that combines a high degree of thrust variation and stable combustion [7] with a high degree of insensitivity [2, 3]. Fig. 1 shows a principle sketch of a GRM that illustrates the basic principles of function. The GP is fed out of the tank by pressure; in most practical cases by a gas dynamic system. A GP valve between the tank and the combustion chamber controls the GP mass flow. The GP is injected into the combustion chamber (CC), liquefies and forms a spray that is burnt. The gas exhausts through the nozzle.

For this system, a widespread family of gelled propellants has been formulated and tested. The scope of variations comprises:

- Blends of fuel liquids which influence
    - The combustion temperature and hence the specific impulse of the propellant
    - The soak temperature range of the gelled propellant for operation and storage
    - The chemical properties of the exhaust gas
- Gelling agents which influence
    - The manufacturability
    - The physical properties of the gelled propellant
    - The combustion process
    - The possibility to suspend particles of different nature
    - The particle content in the exhaust gas
- Additives that serve as combustion catalysts
- Energetic particles that influence
    - The combustion temperature and hence the specific impulse of the GP
    - The GP density and hence the volumetric specific impulse
    - The smoke content of the exhaust gas
    - The chemical properties of the exhaust gas
    - The manufacturability of the GP

All ingredients together influence the chemical and physical stability of the GP over time. And the goal for our development was to have a storage time of the GP in the GRM / GGG system for at least 10 years.

A specific property of the GRM is that the requirements on the mechanical properties of the GP are very relaxed compared to solid rocket propellants. For solid propellants, the mechanical properties including bonding to the case or inhibition layers are design drivers in so far as the integrity of the solid propellant grain has to be maintained over

- All production phases
- All storage, transport and handling phases
- All operational phases

For solid propellant gains, cracks and voids are tolerable only in narrow limits, and big defects can cause severe accidents at operation: If the increase of the combustion surface produces a $p_{CC}$-level beyond the limit strength of the CC a break-up of the case structure upon ignition or during operation is the fatal consequence. The task to secure integrity of a solid propellant grain is a particular challenge because the mechanical parameters, particularly strength and Young´s modulus vary over about two decades over the design temperature range.

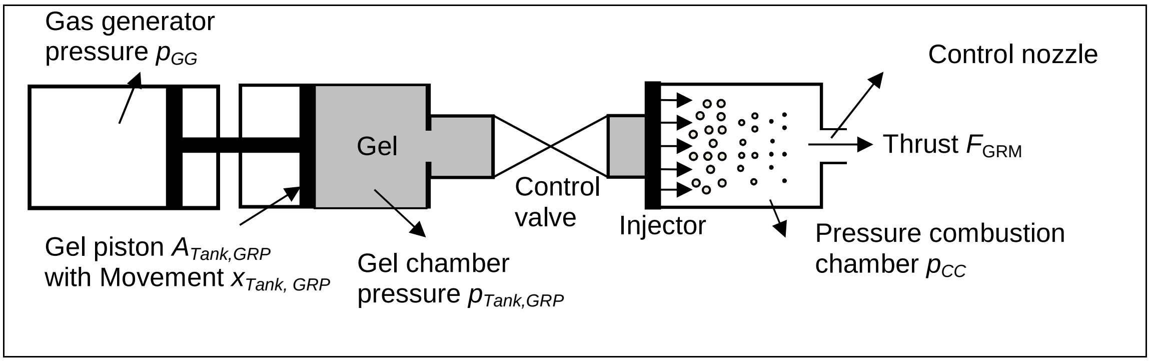


Figure 1: Principle of operation of a GRM [3]

For a GP, the comparatively smooth requirement is that the GP:

- Must not leak out of the tank if the sealing is not perfect or damaged
- Must not spill out of the tank in case of an accident or damage to the tank
- Must not evaporate readily and create combustible mixture with air
- Can be pumped through pipes if set under sufficient pressure

Even if the GP should become quite soft or even liquid, the GRM can fulfil its principal function to produce thrust.

In short, the relaxed requirements on the mechanical properties of GRP contribute significantly to the comparatively easy and cost-effective manufacturing processes of GRP. This is because the tolerances of the manufacturing process parameters and the mechanical parameters of the GRP are large and the expense in quality assurance and laboratory testing is much smaller than what is necessary for solid rocket propellant grains.

According to the specific requirements, within the limits of maximum energy content and minimum combustion temperature $T_c$, any GP can be formulated. For gas generator applications, this variability in $T_c$ allows to adapt $T_c$ to that temperature level that the respective mechanisms can tolerate for the given period of operation time. For rocket application, the focus can be directed to high $I_{spec}$ and high $I_{spec,vol}$ impulse, low plume signature or high turn-down ratio of combustion pressure $p_c$ and thrust.

A controllable monopropellant GRM with all components was demonstrated in 2009 by two perfect flights [8]. Since then activities go on to improve the performance and the functions. For more information see [2 – 5, 7].

In the following the paper describes the propellant development activities and outlines the fields of application of the different propellants.

## 2. Gelled rocket motor propellant development

### 2.1 Pre-requisites on GRP development

A prerequisite of any GRP development in the frame of the German GRM program was to exclude ingredients that could harm people in case of an accident, or a malfunction or a leakage. In military applications, also the impact of propellants that are set free onto the environment has to be minimized in order to minimize the need and expense for environmental clean-up efforts.

This requirement excluded commonly used storable propellants and oxidizers like

- Hydrazine and its derivates (MMH, UDMH)
- Nitric acid (IRFNA)
- Nitrous oxygen and its derivates (NTO, MON)

and ingredients that

- Are not storable under ambient pressure like $N_2O$
- Show even limited intrinsic de-composition effects like $H_2O_2$

The result is that the research and development was from the beginning directed to environmental friendly GRP formulations. Recently, the impact on environment in production, transport, storage and use of materials received increased attention which lead to the REACh regulations. These include of hydrazine into REACh´s list of chemicals of very high concern. Consequently, also in civil rocket motor applications intensive research for “green propellants” has started [9].

As a result of the German MoD´s initial requirements, the German GRP are as “green” as propellants that are storable under ambient pressure and temperature conditions can be.

## 2.2 Method of GRP development

The research on the GRP is mainly done by the Institute of Chemical Technology (FhG-ICT) (see [10, 11] and the literature cited therein). The activities of ICT are carried out in the frame of basic funding of the German MoD and some support by BC. Based on the extensive knowledge, the laboratory equipment and the staff, ICT can draw on a wide range of available and specifically synthesised or modified chemical ingredients. ICT carries out small tests in laboratory scale on

- Manufacturability
- Chemical and physical stability
- Mechanical properties and rheology
- Combustion properties

Promising propellant formulations are taken over by BC and produced in a larger scale that allows to study the behaviour and combustion in a real GRM. For first small scale tests, a modification of BC´s static GRM test facility is done in that cartridges with a small amount of propellant are integrated into the 10-liter GRP tank. Cartridges of 0.3 litres or 1 litre with complete or partial filling can be used. To be able to test also GRP with critical ingredients, a second cartridge can be integrated that contains a purging fluid which is injected into the GRP feeding chain after the GRP is used up. The GRP is fed by pressurized gas into a small GRM with a combustion chamber of 50 mm nominal internal diameter and one injector element. Fig. 2 shows the test facility and Fig. 3 a closer view on the small GRM.

Fig. 4 shows the small GRM in operation, taken from a high-speed video recording with 1000 frames per second recording rate. We see clearly that the exhaust plume produces no smoke, but shows some mild afterburning.

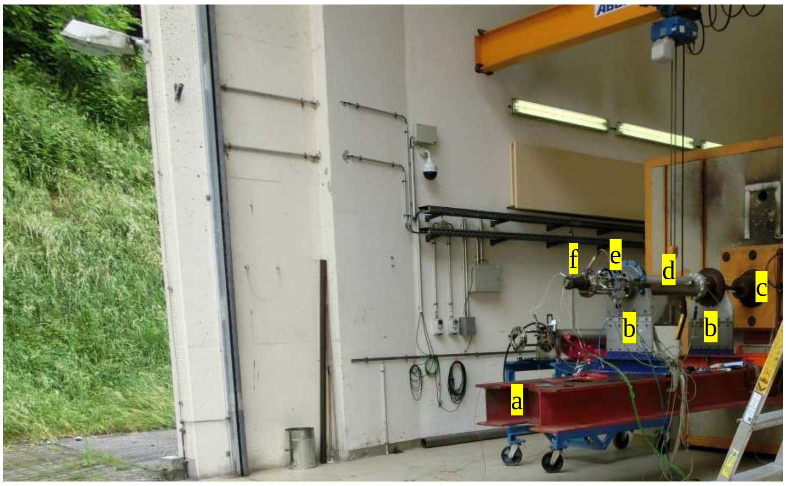


Figure 2: GRM static test facility with small GRM for propellant tests. a) main support, b) flexible support, c) thrust measurement cell, d) GRP tank 10 litres, e) GRP FMFR control devices, f) CC with injector and nozzle.

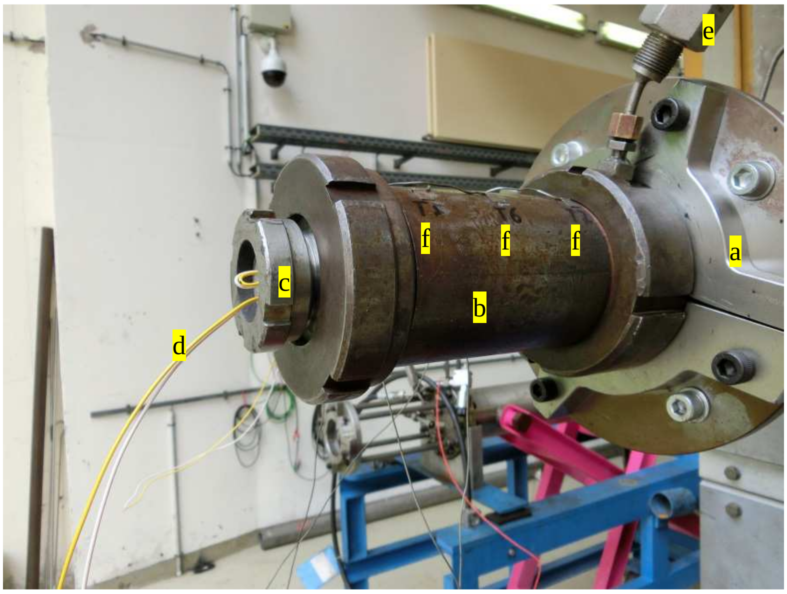


Figure 3: The small GRMC for propellant tests a) injector plate, b) CC, c) nozzle, d) cables of the igniter, e) CC pressure measurement, f) measurement positions for temperature.

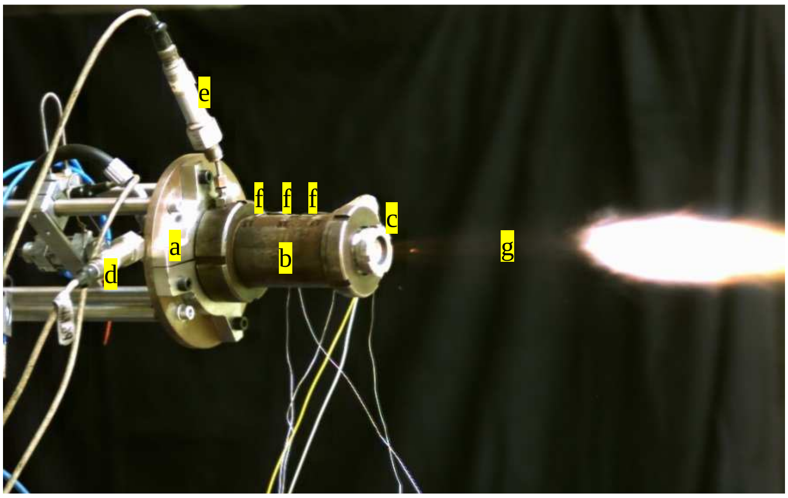


Figure 4: The small GRM in operation, a) injector plate, b) CC, c) nozzle, d) injector pressure measurement, e) CC pressure measurement, f) measurement positions for temperature, g) exhaust plume.

The nominal thrust of this GRM is hardly to determine because it depends on the conditions of operation and the formulation of the GRP. If we mention a “nominal thrust” the respective conditions mean “operation at a maximum fuel mass flow rate at $p_{GRP} - p_{CC}$ = 10 MPa for a typical GRP without energetic particles at atmospheric ambient pressure”. To provide some feeling about the dimensions, the small GRM has a nominal thrust of 300 N with GRP 001 or GRP 006. Starting from this point, the effective thrust can be higher for more powerful GRP or lower for GG-GRP, or if the fuel mass flow rate (FMFR) is turned down.

Whereas the injector elements can be exchanged to modify the injection parameters, all tests up till now showed that this is not necessary. All GRP tested so far could be injected with the same injector elements what underlines the adaptability and variability of the GRM system.

The small scale tests have the advantage that

- Expensive ingredients can be tested even if the probability of success is limited
- The requirements on the hazard analysis for the production and the test are less demanding than for a bigger mass

- The small propellant mass is sufficient to determine the data needed to carry out a hazard analysis for the production of larger quantities

If these small scale tests yield satisfying results, a larger volume of the propellant, usually 10 litres, is produced for a test on the GRM facility with a larger GRM. In most cases we use a CC of the size of the free-flight demonstrator GRM, which is designed for a nominal thrust of 5.5 kN with an injector head containing 18 injector elements. Variable variants of this CC outline allow to use injector heads with another number of injector elements and different thrust nozzle dimensions and geometries. Fig. 5 shows a variant of this GRM on the test stand with a 10 litres piston tank. Fig. 5 shows also the safety measures attached to the test: A collection pan is in place under the nozzle opening to collect GRP that might leave the nozzle if the combustion is not active, and a plastic sheet covers the surface of the blast yard to prevent contact of accidentally unburnt GRP with the surface.

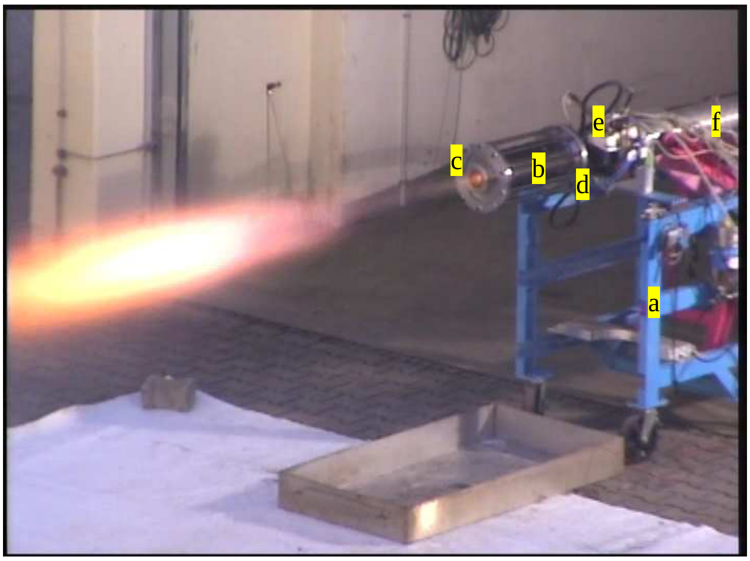


Fig. 5: Test setup with variable GRM with 5.5 kN nominal thrust and a tank of 10 litres, a) GRM test stand, b) CC, c) end plate with nozzle, d) injector head, e) GRP flow control, f) GRP piston tank 10 litres.

For tests with a long operation time, an additional re-usable membrane tank with 20 litres volume is available and allows to increase the total $V_{GRP}$ to 30 litres. Fig. 6 shows a test setup with the two GRP tanks and a CC with a nominal thrust of 5.5 kN.

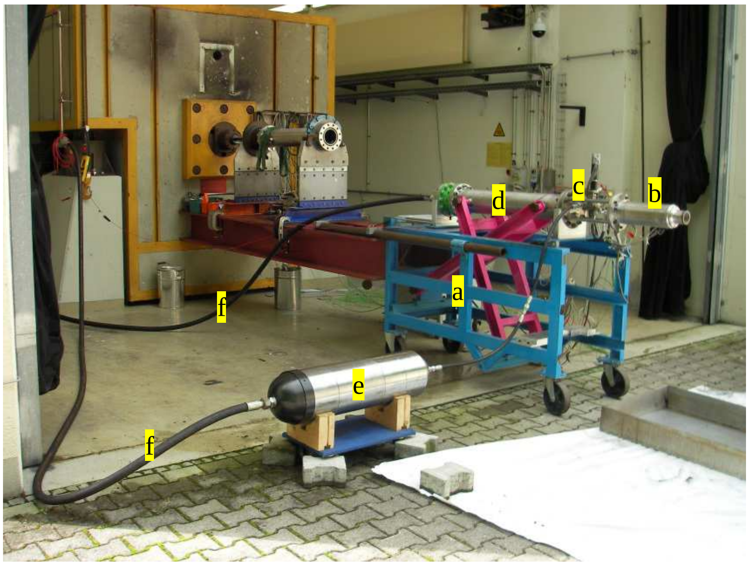


Figure 6: GRM test setup with two GRP tanks and a CC with a nominal thrust of 5.5 kN, a) GRM test stand, b) CC with nozzle, c) GRP flow control, d) GRP piston tank 10 litres, e) GRP membrane tank 20 litres, f) high-pressure air supply tubes.

## 3. The GRM monopropellant family

The first result of ICT´s activity was GRP 001 which was used for the first static tests and the free-flight demonstration [7] (see Table 1). GRP 001 does not contain energetic particles and the picture of the free-flight missile just after launch in Fig. 7 shows that the GRM produces very little smoke and, in essence, a transparent plume. The $I_{spec}$ of about 2250 m/s for a 70:1 expansion with an adapted nozzle into atmospheric conditions is comparable or slightly better than the $I_{spec}$ of double-base solid propellants.

Advantges of GRP 001 are:

- Good manufacturability
- Affordable ingredients
- Good degree of insensitivity

A disadvantage of GRP 001 is that it does not burn at low $p_c$. Hence, it is not suited for applications that require a wide operational range of $p_c$ or a low $p_c$.
If the criterion to operate even at low $p_c$ should be of minor relevance, e. g. for GRM for launcher stages for sounding rockets, GRP 001 can be a good choice because of its low price.

An increase of performance was achieved by addition of particles which yielded GRP 002 with higher $I_{spec}$ and also density (see Tab. 1). GRP 002 could be operated in the same CC and with the same injectors as GRP 001.

Table 1: Key parameters of the GRP family

| Gel | $I_{sp}$ [Ns/Kg] $p_c / p_\infty = 70:1$ | $T_c$ [K] | $\rho$ **[g/cm$^3$]** |
|---|---|---|---|
| 001 | 2248 | 2199 | 1.13 |
| 002 | 2487 | 2795 | 1.31 |
| 003 | 2236 | 2089 | 1.18 |
| 004 | 2586 | 2910 | 1.28 |
| 005 | 2080 | 1883 | 1.17 |
| 006 | 2182 | 1981 | 1.16 |
| 007 | 1900 | 1396 | 1.11 |
| 008 | 1878 | 1375 | 1.09 |
| 009 | 2143 | 1904 | 1.19 |
| 013 | 2290 | 2536 | 1.41 |
| 014 | 2178 | 1857 | 1,14 |
| 015 | 2467 | 2770 | 1.38 |
| 016 | 2465 | 2809 | 1.38 |
| 017 | 2423 | 2650 | 1.38 |
| 018 | 2135 | 2574 | 1.42 |
| 019 | 1990 | 1438 | 1,11 |
| 025 | 2588 | 3080 | 1.49 |
| 026 | 2622 | 3150 | 1.49 |
| 039 | 2629 | 3180 | 1.55 |

Figure 7: GRM demonstrator missile just after launch. Propellant: GRP 001, GRM with 5.5 kN nominal thrust [7]

Introduction of another gelling agent in GRP 003 and GRP 004 resulted in a lower minimum $p_c$ whereas the $I_{spec}$ and $\rho$ are not significantly changed. GRP 003 is the propellant with low signature without energetic particle content and GRP 004 is the variant with energetic particles that increase $I_{spec}$ and $\rho$ and produce a contrail.

A further reduction of $p_{c,min}$ was achieved with the addition of an additive. The best result is represented by GRP 006, which burns at $p_{c,min}$ = 0.6 MPa [3, 12]. GRP 006 has a low signature and the exhaust contains no particles that produce deposits. Hence, GRP 006 is also well suited as GGG propellant, for example in ACS or DACS applications [12]. In space applications the low $p_{c,min}$ allows controllable operation at low overall pressure level which saves structural mass [3].

For GGG applications that cannot tolerate the $T_c$ of GRP 006, the fuel blends can be modified to adapt the $T_c$ to that temperature level that the mechanical structures can endure over the foreseen operation cycle. GRP 007 and GRP 008 are examples for low-temperature GGG propellants. Any $T_c$ between the values given for GRP 008 and the other GRP that produce smoke- and particle-free gas can be realized. GRP 009 is a further variant with intermediate $T_c$, also for GGG applications. GRP 014 has a lower $T_c$ than GRP 006 but almost the same $I_{spec}$.

GRP 013 is a propellant with energetic particles that increase the density and produce few particles in the exhaust, but with moderate $I_{spec}$.

GRP 015, GRP 016 and GRP 017 are propellants that have a high $I_{spec}$. like that of high-performance solid propellants at a lower $T_c$ and comparatively high $\rho$ of about 1380 kg/m$^3$. These propellants contain the same energetic particles, but differ in the selected gelling agents and additives.

GRP 018 is a propellant with high density that does not produce particle deposits, but the comparatively high $T_c$ compared to the limited $I_{spec}$ do not make it a favourite if it comes to propellant selection.

GRP 019 is a propellant that can be manufactured most easily, but which remains quite soft even after the gelation process is finished. Because of the very easy manufacturability and the high turn-around rate in testing it is used for static tests of components, if the function is under investigation and less the specific performance [7]. Like GRP 007 and 008, from the thermodynamic point of view it also would make a good propellant for ACS and DACS applications.

GRP 025, GRP 026 and GRP 039 are recent results of the activities to develop GRP with high $I_{spec}$ and in the same turn high $\rho$. This is achieved by the addition of energetic particles. The $I_{spec}$ is higher than that of current high-performance composite propellants and the $\rho$ is quite high compared to that of other liquid propellants. In turn, the $T_c$ is well above 3000 K.

Please keep in mind that all these propellants were tested with the same combustion chambers and the same injector elements. This shows that the very different propellants have similar spraying and combustion characteristics. This also shows that the combination of hardware and propellant can be selected very freely representing at its best the sense of a modular propulsion system.

## 4. Summary and outlook

The transfer of GRP that have been developed at the FhG ICT in laboratory scale to applications in real GRM starts with the manufacturing of small amounts that are sufficient to operate a small variable GRM. Tests that support hazard analyses of the respective GRP are done in parallel to the evaluation of the manufacturing parameters. After satisfying results with respect to:

- Manufacturability
- Hazard potential
- Chemical and physical stability
- Performance in the small GRM tests

the GRP is tested in larger quantities in larger GRM, mostly a using a CC for 5.5 kN of nominal thrust.

In the second chapter the paper presents the family of monopropellant GRM and gives information on the specific properties and proposed applications. The good variability of the formulation allows to taylor the GRP specifically for the application in view.

Current activities in GRP development aim to improve the $I_{spec}$ and $I_{spec,vol}$, either by introducing more energetic ingredients into the monopropellant GRP or to develop bi-propellant systems. For the latter, environmentally friendly hypergolic propellant and oxidizer are also a matter of basic research at ICT [13].

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