

# ROCKET PROPULSION WITH GELLED PROPELLANTS FOR SOUNDING ROCKETS

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## ABSTRACT

Gelled propellant rocket motor (GRM) technology development started in Germany in 2000 and led to two perfectly successful demonstration flights of a throttleable rocket motor burning a gelled monopropellant in December 2009. The introduction gives an overview on the technology and its special functional properties. The main body of the paper outlines potential applications of the GRM technology for sounding rockets. A concept design is presented for a kick stage / trajectory insert stage motor, where the specific advantages of GRM: thrust modulation, shut-off capability and cost advantages should outweigh shortcomings like the moderate specific impulse. Other applications can be first stage motors or attitude control systems.

## 1. INTRODUCTION

### 1.1. Gelled Propellant Rocket Motor Technology

A gelled propellant rocket motor (GRM) (see [1, 2] and the literature cited therein) combines the advantages of a solid rocket motor (SRM) - easy handling and long storage time - with those of a liquid rocket motor (LRM) - thrust modulation / shut-off capability and the potential for long operation times. It performs better than both solid and liquid rockets in terms of

- Safety – no explosives, no liquids
- Insensitivity in case of accidents, because the propellants are no explosives, there is no spillage in case of leakage or perforation of the tanks, and gels have much lower vapour pressure than liquid fuels and hence a significantly lower evaporation rate in case of destruction of the tank.

An other advantage of gels is that solid particles can be suspended without the risk of sedimentation during long storage times. This increases the density and particularly the  $I_{\text{spec,vol}}$  of the propellant, but increases the production of smoke.

Shortcomings are the need for a powerful tank pressurization system and a tank design that withstands high internal pressure.

The principle of function, see Fig. 1, is based on the fact that the gelled propellant (GP) is “solid” in the tank and liquefied upon injection into the combustion chamber (CC) by high shear rates (see for example [3] and the literature cited therein). Through its shear-tinning behaviour the gel assumes the nature of a liquid and almost the associated low viscosity of the basic liquids mixture [4]. The spraying and combustion process is in principle similar to that of a LRM burning storable propellants while some peculiarities with respect to spraying and combustion have to be addressed [2].

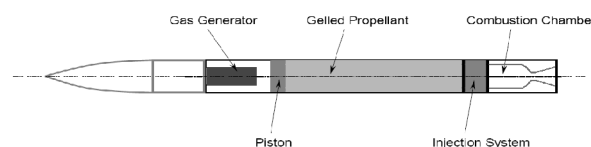


Fig. 1: Principal sketch of a GRM with a solid fuel gas generator and a tank with a piston [2].

While by nature GP cannot be pumped like a liquid propellant (LP), it has to be fed from the tank to the injector by pressure. For short operation times solid propellant gas generators (SPGG) have been demonstrated [5, 6, 7]. For longer operation times the thermal insulation of the tank and the piston against the heat transfer from the hot gas into the structures may become a mass driver. Hence, a pressurization system using highly compressed gas, preferably helium, is favoured. This allows to build a lightweight tank from carbon fibre reinforced resin (CFRR) and a lightweight piston or membrane without heat shield [8]. Please notice that GP does not move within the tank due to acceleration or spinning effects like LP.

### 1.2. The German Gelled Propellant Rocket Motor Program

After preliminary activities in 1999 the German Gel Technology Program (GGTP) [2, 9, 10] was initiated in 2000 as an initiative of Bayern-Chemie (BC), DLR Institute of Space Propulsion (IRA), FhG Institute of

Chemical Technology ICT, German armed forces proving grounds and the German MoD. The goal was to develop a thorough understanding of the technology and to fly a missile with GRM in 2009, which was achieved by two perfect ballistic flights with a monopropellant GRM with pre-programmed thrust modulation [7]. The concept of the missile follows the principle of Fig. 1. Fig. 2 shows the missile design and the main components in more detail.

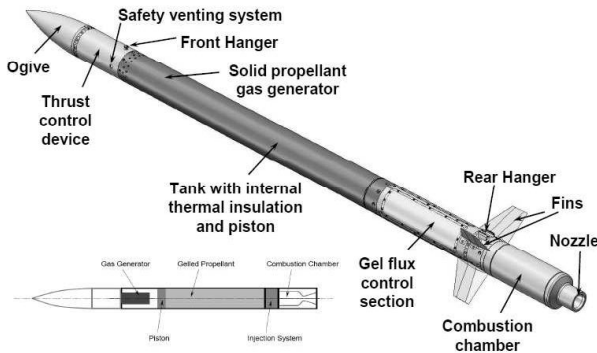


Fig. 2: Design and major components of the flight demonstrator missile [2].

Over the time of operation, a specifically designed SPGG solid propellant gas generator [6, 7] delivers the propellant feeding pressure within pre-determined limits while the GP is expelled by a piston and fed into the combustion chamber. Because the pressure variation is too slow to be used for propellant flow control, a control valve controls the GP mass flow that is injected into the combustion chamber through an injector head. A safety device vents the tank in case of a deliberate launch abort, when the tank is empty and upon impact of the missile on the ground. Thrust modulation is done by a pre-programmed operation of the GP valve, ignition by a SP igniter positioned in the CC.

The calibre of the demonstrator missile is 135 mm, the length 3042 mm, the launch mass 75 kg, the propellant mass 12 kg and the nominal thrust 5,5 kN. Fig. 3 shows the demonstrator missile at launch.

Special features of the German GRM technology, in addition to the above mentioned general ones, are:

- A monopropellant system with stable start, combustion and throttling behaviour
- Demonstration of the predicted performance parameters, like specific impulse
- Environmental friendliness of propellant and exhaust gas
- Little primary and secondary smoke if no solid additives are used
- Good handling, transport and storage properties
- Long storage time, like SP

- Lower cost for the GP, compared to solid propellant (SP) or other storable propellants



Fig. 3: The GRM demonstrator missile at launch [2].

Other functions that have been demonstrated by static tests are:

- Ignition by an external gas lancet
- Gels with different gelling agents
- Gels with aluminium particles. The  $I_{spec}$  measured at atmospheric pressure increases from 2150 m/s (220 s) to 2400 m/s (245 s), but the plume contains primary smoke.
- GRMs with nominal thrust levels between 300 and 6000 N.

The ignition sequence using a SP igniter is as follows:

1. Pressurization of the tank, by ignition of the SPGG or by opening the connection to a high pressure reservoir
2. When the tank pressure has reached its operational level: initiation of the SP igniter
3. When the combustion chamber pressure reaches the threshold level for ignition: opening of the GP valve

This sequence can be interrupted at any time without risk to lose the missile. Because three independent conditions are needed to put the GRM into operation:

- Pressurization of the GP tank
- Initiation of the igniter
- Opening of the GP valve

a specific safety and arm unit (SAU) as for SRM is not needed.

Current activities in Germany aim to improve functional and performance parameters, like turn-down ratio, specific impulse, propellant density, run time and operational temperature range. In what follows, we refer as far as possible to the currently verified state of technology. If non-verified items or parameters are incorporated, these are explicitly designated. The idea of this paper is to show what can be done with currently or near-term available means for near- or mean-term applications in fields where one or more of the above

mentioned advantageous of a GRM are driving parameters.

## 2. GELLED PROPELLANT ROCKET MOTOR TECHNOLOGY FOR SOUNDING ROCKETS

### 2.1. General Aspects of the use of Gelled Propellant Rocket Motor Technology

The GRM technology in the version flown by BC has benefits compared to SRM or LRM technology if:

- Thrust modulation s required
- Insensitivity, good handling and transport properties are more important than a minimum launch mass or a minimum propulsion system volume.
- Environmentally friendliness with respect to propellant and combustion products is important.
- The combustion time is long, say in the order of a minute or more. In this case the separation of tank and combustion chamber has the advantage that, compared to a SRM where tank and combustion chamber are identical, the tank can be kept cool [8] without needing mass-consuming thermal insulation. Only the comparatively small combustion chamber is subjected to heating.
- Cost-efficiency is an important parameter. The per kilogram price of the current base line monopropellant GP1 without suspended particles is lower than that of SP and storable or cryogenic LP.

Shortcomings of the GRM technology in general are:

- A high pressure level in the tank and hence a high mass of the tank structure
- The mass needed for a powerful pressurization device, say gas tanks. If a solid fuel gas generator is used, the tank will need an internal heat shield which also affects the mass budget

Shortcomings of the actually available GRM technology are:

- A moderate specific impulse
- A limited temperature range from -30 °C to +71 °C.

Hence, GRM technology offers solutions not for extremely performance driven applications like main propulsion systems for air-defense missiles, orbital launch vehicles or satellite station-keeping RM, but for applications where easy handling, insensitivity, cost-efficiency and thrust modulation / shut-off capability are design drivers.

Tables 1 - 3 give a qualitative comparative (the brighter the fields – the better the properties) overview on key parameters of GRM, SRM, LRM with cryogenic and storable liquid propellants and RM that operate on gaseous fuel and liquid oxidizer (GF/LOX-RM). We see that particular explosion risks are associated to

propellants that are stored in gaseous state or can evaporate rapidly. Conventional storable liquid fuels, if set free, endanger people or the environment if they do not burn away completely. Solid fuels are explosives by nature, but need a comparatively significant stimulus for accidental initiation. Gelled fuels have a very low evaporation rate and -surface, burn hardly under ambient conditions, create no explosive vapors and seep not away into the soil.

Tables 2 and 3 show that the low hazard potential and the uncritical ground handling of the GP are key discriminators of GRM technology.

	GCH <sub>4</sub> / LO <sub>2</sub>	LH <sub>2</sub> / LO <sub>2</sub> LCH <sub>4</sub> / LO <sub>2</sub>	MMH/MON Hydrazine/MON	SRM	GRM
Tank pressurization (if no pumps are used)	Permanent High (H <sub>2</sub> ,CH <sub>4</sub> ) Standby: Low (LO <sub>2</sub> )	Standby: Low Operation: High	Standby: Low Operation: High	Standby: No Operation: High	Standby: Low Operation: High
Tank thermal insulation	Yes (LO <sub>2</sub> )	Yes	No	Yes Heatshield	No
Propellant evaporation	Storage: Yes (LO <sub>2</sub> )	Storage: Yes	No	No	No
Number of tanks	2	2	2	1, no combustion chamber	1
Volume of tanks	>1	4 / 1	1	< 1	1 (Reference)

Table 1: Comparison of key tank and propellant storage parameters for GRM, SRM, LRM and GF/LOX-RM.

	GCH <sub>4</sub> / LO <sub>2</sub>	LH <sub>2</sub> / LO <sub>2</sub> LCH <sub>4</sub> / LO <sub>2</sub>	MMH/MON Hydrazine/MON	SRM	GRM
Effect of leakage or perforation	Fire Explosion	Fire Explosion	Fire Pollution	None on safety	Little Discharge
Emergency depressurization	No	With discharge	Yes	N/A	Yes
Residues after motor shut-off	Possible to retain	Evaporate	Keep	No shut-off possible	Keep
Behaviour at launch pad accident	Evaporation (Explosion)	Evaporation (Explosion)	Spillage (Fire)	Burning or Explosion	Little discharge small fire
Behaviour at fire on launch pad	Burning (Explosion)	Burning (Explosion)	Burning of vapour	Burning or Explosion	Burning of vapour

Table 2: Safety aspects of GRM, SRM, LRM and GF/LOX-RM.

	GCH <sub>4</sub> / LO <sub>2</sub>	LH <sub>2</sub> / LO <sub>2</sub> LCH <sub>4</sub> / LO <sub>2</sub>	MMH/MON Hydrazine/MON	SRM	GRM
Storage – special requirements	Pressure Kryo	Kryo	Sealed	No	No
Pipes – special requirements	High pressure Kryo	Kryo	Sealed	No	No
Joints – special requirements	High pressure Kryo	Kryo	No	No	No
Special materials	Yes (LO <sub>2</sub> )	Yes (LO <sub>2</sub> , LH <sub>2</sub> )	No	No	No
Safety regulations	Significant	Significant	Significant	High	Moderate
De-pressurization	No	Yes (efflux)	N/A	N/A	N/A

Table 3: Ground operation aspects of GRM, SRM, LRM and GF/LOX-RM.

### 2.2. Kick- or Trajectory Insertion Rocket Motors with Shut-off or Thrust Adaptation Capability

For some sub-orbital or even orbital missions it is important that the payload is put on a trajectory very precisely in terms of the course of the trajectory and the speed at a given point. Solid rocket launchers, which come more and more into use, are very compact and easy to handle on the launch pad, but have no means to precisely control the burn-out velocity. Hence, a small

stage using a RM with thrust modulation or shut-down capability has to be used. The purpose of this small stage is to deliver a small velocity increment that bridges the gap between the burn-out velocity of the main launcher and the required trajectory insert velocity and to add some potential energy if required. The dimensions of the trajectory-insertion motor follows the concept presented in [11].

Fig. 4 illustrates the layout of such a motor by a principal sketch of such a trajectory insertion stage. In order to provide a feeling for the dimensions and performance parameters, tab. 4 gives some data based on conservative approaches. Please notice, that the volume of the tank and the thrust of the RM can be varied independently according to the specific requirements and that bigger or smaller components can be chosen. The outer shell of the stage is indicated, but interfaces between the shell and the components of the GRM are not detailed in the frame of this study. The components are arranged as symmetrically as possible in some space-economic way, but other arrangements are possible.

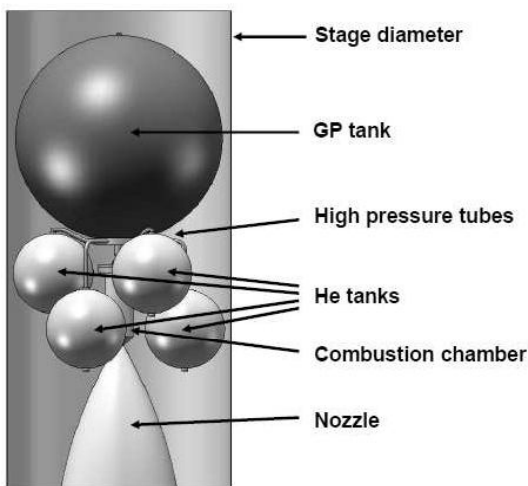


Fig. 4: Concept of a controllable trajectory insertion stage with GRM.

Due to the long maximum time of operation, i.e. 280 s at a conservatively estimated mass flow of 4 kg/s which produces the nominal vacuum thrust of 10 kN, a cold gas tank pressurization system using high-pressure Helium is chosen. The 6 He tanks and the helium are heavier than a solid fuel gas generator, but the GP tank needs no heat shield. For the monopropellant a single propellant tank is sufficient, while multiple tanks can be used if that should be of advantage. According to the parameters of the presently operational system, the nominal combustion pressure is 10 MPa and the tank pressure is 20 MPa. The initial pressure of the He-tanks is 100 MPa. The He is fed into the GP tank through a

pressure reducer which maintains the constant GP tank pressure of 20 MPa independent of the GP mass flow. Within the tank, the GP and the He are separated by a flexible membrane. While membrane tanks have not yet been used or developed for BC's GRM programme, practicable membrane tank designs should be possible and activities at BC are ongoing to identify materials that are compatible with the GP. All tanks for GP and He are made of carbon fibre reinforced resin (CFRR) wound over a thin Aluminium liner. Fig. 5 shows a longitudinal cut through the assembly.

Nominal thrust	10 kN
Burning time at nominal thrust	280 s
Nominal CC pressure	10 MPa
Nozzle area ratio	580
Nominal GP mass flow	4 kg/s
GP tank pressure	20 MPa
Max GP mass	1130 kg
Maximum He tank pressure	100 MPa
Maximum He mass (6 tanks)	45 kg
He tank volume	6*42 l
Total mass	1700 kg
Inert GP tank mass	250 kg
Inert He tank mass	175 kg
Mass of CC, nozzle, injector and GP control valve	65 kg
Mass of tubings	35 kg

Table 4: Data of the trajectory insertion stage concept of figs. 4 and 5

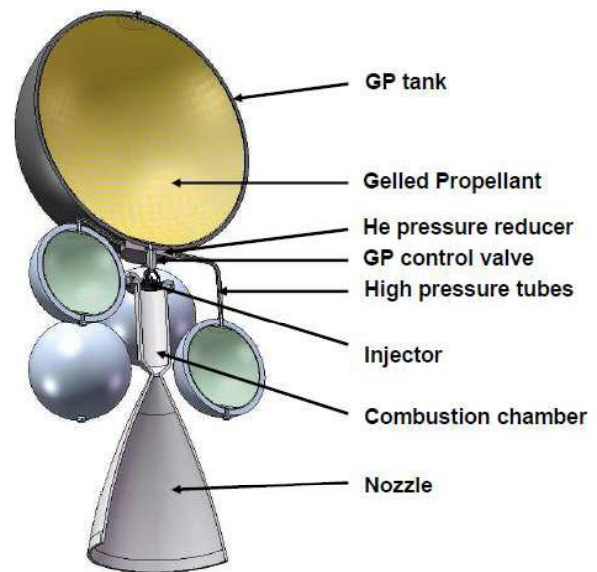


Fig. 5: Longitudinal cut through the concept of a controllable trajectory insertion stage with GRM.

The flow of the GP is controlled by a valve between the tank outlet and the injector, providing thrust control, if required, and a shut-down capability.

The injector, CC and nozzle are designed for a nominal vacuum thrust of 10 kN. This is not far away from the main sea level (MSL) thrust of 5,5 kN of the flight demonstrator motor. The up-scaling is mainly done by adapting the number of injectors, the size of the CC and the nozzle throat cross-section area. The concept of the CC and the nozzle shown is based on the use of fibre reinforced ceramics, because that material needs no cooling – a feature that seems not to be practical with GP. Studies on all-ceramic CC and nozzle are ongoing, but the verification of a design is still to be done. The CC design of the demonstrator using a metal case with internal heat shield worked very well but is not yet verified for minutes of operation.

If thrust vectoring should be required, a movable combustion chamber could be a reasonable option, evading the critical interface between a fixed CC and a movable nozzle as well as the reduction of the axial thrust that is inevitably associated to jet vanes and flaps.

The numbers given in Tab. 4 represent a set of conservative approaches and assumptions. Mass reduction potentials can be expected by the following measures:

- Reduction of the overall pressure level. The reduction of the nominal tank pressure to 10 MPa and the motor pressure to 6 MPa should:
  - o Reduce the GP tank mass by roughly a factor of two
  - o Reduce the He tank mass by roughly a factor of two
  - o Reduce the He gas mass by a factor of two
- Detailed optimization of the structures of tanks and interfaces (polar bosses, joints, tubes) to reduce the mass

The reduced pressure within the combustion chamber has to be compensated by increased size; hence, no significant mass reduction is expected for CC and nozzle. The total mass savings potential amounts to about 250 kg, then yielding a total mass of about 1450 kg and a propellant mass fraction of 0,78 for the GRM components without outer shell structure and interfaces..

For applications where the mass of the payload or the required velocity increment vary, the GRM can be configured in that way that the propellant mass is adapted to the mission within the tank's capacity limit. Similarly, the thrust of the GRM can be adapted to the mission requirements within the thrust limits of the GRM.

In short: one trajectory insertion GRM design can be used for a wide variety of missions, and a set of modularly usable components, especially GP tanks and He tanks of different volume and GRMs of different thrust categories allow to tailor a trajectory insertion

motor from verified components according to specific mission requirements.

The modular system, for example, allows also to carry out full functional checkout flight tests of the GRM with a smaller tank and accordingly a smaller and more affordable launcher; thus leaving only the big tank to be verified with the full-size launcher assembly.

The biggest steps to be done for the development of the trajectory insertion stage are for the development of the GP tank and the full-ceramic CC and nozzle.

The filling of the GP can can be done near the launch site or at the manufacturer's facilities. The same holds for the production of the GP, because the investments for a GP production facility are less than those needed to produce SP.

The safety features of the GRM flight demonstrator missile can be used directly for the trajectory insertion stage: proven means to de-pressurize the GP tank and the start sequence.

The concept shown has a SP igniter in the CC. A gas igniter might be a solution to build a re-ignitable GRM. For this, the necessary means do not only comprise a gas supply and ignition device for the igniter, but as well specific procedures for the cutting-off of the GP flow and the correct re-start of the combustion process.

### **2.3. Insensitive and Environmentally Friendly Stages for Sounding Rockets**

The concept layout of a launcher stage for a sounding rocket comprises the same set of components as that shown for the kick stage above. The major differences are:

- A slender GP tank instead of a spherical or nearly spherical one. If the length/diameter ratio is high enough, a moving piston may be more effective than a membrane
- For a slender design, the high-pressure gas tank would be placed in front, say on top of the GP tank using the same outer diameter. Fig. 6 shows such a configuration for a tactical missile propulsion concept
- The nozzle divergent has to be cut to adapt the expansion ratio to the ambient pressure level, making the nozzle more compact
- The GRM thrust has to be increased significantly, i.e. by an order of magnitude. Within the demonstrated thrust regime between 300 N and 6000 N, scaling laws taking into account the number of injectors and CC dimensions work very well. Taking into account that extrapolations over one order of magnitude are critical by nature, there

nevertheless is a fair chance that the scaling laws work also in the up-scaling direction.

With respect to

- Modularity
- Procedures
- Handling and storage properties

the same statements as for the kick-motor are valid.

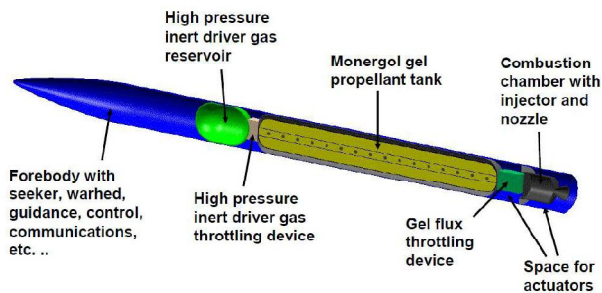


Fig. 6: Design concept of a slender GRM with a bladder tank for a missile [8].

### 3. SUMMARY

Gelled propellant rocket motor technology as it has been flight demonstrated in the frame of the German GRM program offers the potential to build throttleable, insensitive and environmentally friendly rockets with good handling and storage properties for applications where ultimate specific ballistic performance is not the key design driver. Another advantage should be the affordable propellant. Applications may be kick-stages with thrust control and/or shut-off capability, launcher stages or direction and attitude control systems.

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