

Introduction to Hybrid Rockets

Why we build one, how it works, and what makes it hard — written for new members of the Phobos project

What we are building

Phobos is a hybrid rocket, designed and built by students. It burns nitrous oxide (N_2O) against a grain of paraffin wax. The plan is to fly it at the European Rocketry Challenge in Portugal in 2027, in the 3000 m target category. We have four subteams: Propulsion, Electronics, Structures, Media.

1. Three ways to burn something in a rocket

Every chemical rocket does the same thing: it mixes a fuel with an oxidiser, burns them to produce a lot of hot gas, and throws that gas out of a nozzle. The three families of chemical rocket differ only in what physical state the propellants are stored in.

- **Solid motors** carry fuel and oxidiser already mixed together and cast into one rubbery block. They are simple and dense, but they are essentially a large firework: once lit, they cannot be throttled or shut down, and a crack in the grain adds burning surface area, which raises chamber pressure, which raises the burn rate further. That feedback loop is how solid motors burst.
- **Liquid engines** keep fuel and oxidiser in separate tanks and meter them into the chamber through an injector. They give the best performance and can be throttled and shut down, but they need two feed systems, two tanks, and a precision injector whose channels of fuel and oxidiser are separated only by thin metal walls. When an injector fails, the fire usually travels back up the plumbing.
- **Hybrids** split the difference: a liquid (or self-pressurising liquefied gas) oxidiser in a tank, and a solid fuel grain sitting inside the combustion chamber. The two only ever meet inside the chamber.

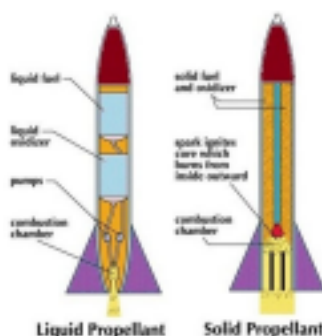


Figure 1 – Liquid and solid propellant rockets. A hybrid stores the oxidiser like the left-hand rocket and the fuel like the right-hand one.

2. Why CAESAR builds a hybrid

The short answer is that it is the only one of the three a student association in Sweden can design, build, store, transport and test without the paperwork becoming the project.

Start with the regulatory side, because that is what actually decided it. A cast solid propellant grain is an energetic material — fuel and oxidiser pre-mixed — and in Sweden it falls under the legislation on flammable and explosive goods. That means permits, approved storage, and a named responsible person. A hybrid's fuel grain is a block of candle wax. On its own it is inert and it will not detonate. The oxidiser is a bottled liquefied gas, a well-understood industrial commodity that a great many workshops already handle. It is worth stating this precisely rather than repeating the shorthand that solids and liquids are "banned". They are not banned. They are regulated in a way a student project cannot absorb.

The test stand is the second reason. We can close a valve and stop the burn — which, the first time something sounds wrong through the speakers, is worth more than any performance number. And because the fuel and the oxidiser are separated by the chamber wall right up to the moment of combustion, a small crack in the grain

does nothing at all. There is no flow through it, so nothing burns in it.

Then there is cost. Paraffin is cheap and you can cast it in what is essentially a kitchen setup. N_2O pushes itself out of the tank, so there is no pressurant system, no turbopump, and no elaborate injector to machine.

You should know the trade from day one, though, because you will be asked about it in every review: hybrids burn less efficiently than liquids, and the mixture ratio drifts as the burn goes on. Sections 4 and 6 explain why, and neither one goes away.

3. Anatomy of a hybrid engine

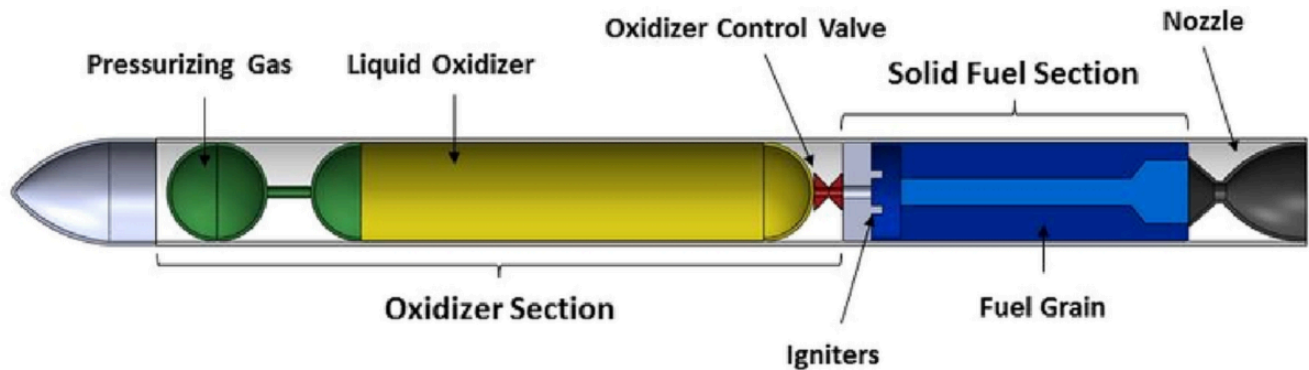


Figure 2 – The whole system: oxidiser tank, control valve, injector, igniter, fuel grain, nozzle.

Walking downstream, these are the parts you will hear named in every Propulsion meeting:

Run tank — the flight tank of oxidiser, filled on the ground from a larger commercial fill tank. In a forward hybrid it is wrong to call this the fuel tank, the fuel is the wax down in the chamber. People slip on this constantly.

Main valve — the one component that makes a hybrid safe. It can stop the burn.

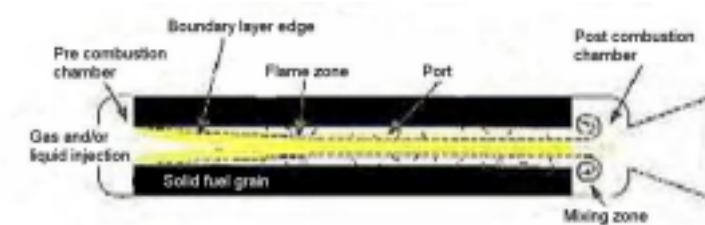
Injector — a plate of small holes that meters the oxidiser and breaks it into a spray. Since only one propellant passes through it, it is far simpler than a liquid engine's.

Pre-combustion chamber — an empty volume between injector and grain, so the oxidiser has room to atomise and vaporise before it enters the port. Liquid droplets making it into the port are bad news: they punch straight through the boundary layer and blast small craters in the grain, which you will see afterwards as pressure roughness.

Fuel grain and port — the port is the hole down the middle of the grain. Its wall is the burning surface, and it grows outwards for the whole burn.

Post-combustion chamber — another empty volume, this time between grain and nozzle. The flow leaving the port is fuel-rich at the wall and oxidiser-rich in the core, and the toroidal vortex trapped here mixes the two. Most of the combustion efficiency we would otherwise lose is recovered in this one empty space.

Nozzle — turns hot high-pressure gas into directed velocity. Graphite, in most student hybrids.



hybrids.

Figure 3 – Section through the chamber. Note that the flame does not sit on the fuel surface: it floats inside the boundary layer, and that the chamber has empty volumes before and after the grain.

4. What actually happens inside the combustion chamber

This is the part that surprises people. A hybrid does not burn like a candle wick, and it does not burn like a solid motor. The combustion happens inside the boundary layer of the gas travelling down the port.

Gas flowing along a wall does not slip past it. At the surface the velocity is zero, and it climbs to the free-stream value across a thin region — the boundary layer. A few centimetres down the port that layer trips from smooth to chaotic, and it is the turbulence that drags hot gas down onto the fuel.

From there the chain runs like this. Hot gas in the turbulent boundary layer conducts heat into the top of the grain, by forced convection, for a plain wax or plastic grain, radiation is a second-order effect. The surface heats past its melting point and a very thin liquid melt layer forms — for paraffin, a few tenths of a millimetre, constantly replenished from below and stripped from above. That melt vaporises and the vapour is carried out into the port flow. (Plastics do not melt so much as crack: the long polymer chains break into shorter gaseous hydrocarbons, which is pyrolysis.)

For low-viscosity melts like paraffin something else happens on top of that. The gas blowing over the liquid raises ripples and roll waves, and droplets are torn off the crests the way spray comes off a wave. This is **entrainment**, and it is the whole reason paraffin regresses several times faster than plastic: the fuel does not have to be vaporised in order to leave the surface.

Fuel vapour and oxidiser then meet somewhere in the middle, at whatever height in the boundary layer the mixture happens to be close to stoichiometric, and burn there in a thin sheet — a macro diffusion flame.

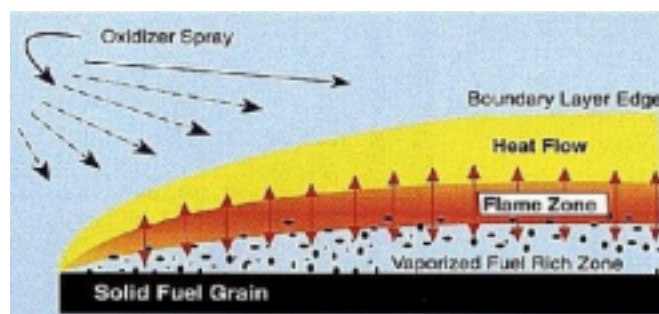


Figure 4 – The flame zone floats between a fuel-rich layer at the wall and the oxidiser-rich core. Heat flows down to the grain, fuel vapour flows up to the flame.

Two things follow from this, and both matter to us. Because the flame stands off the surface, the burning rate is almost independent of chamber pressure — the opposite of a solid motor, where pressure and burn rate feed each other. And because fuel and oxidiser have to *find* each other by diffusion and turbulent mixing instead of arriving pre-mixed, a hybrid is inherently less efficient than a liquid engine. The post-combustion chamber exists to claw part of that back.

5. Why paraffin, and what it costs us

The classical hybrid fuels are plastics: HTPB, PMMA, HDPE, nylon. They are strong, well characterised and entirely safe to have in a workshop. Their problem is that they regress slowly. To get enough fuel flow at any useful thrust you need either a very long, thin grain, or several ports burning in parallel.



Figure 6 – A multi-port grain with structural webs. As the ports meet, slivers of fuel can break free and block the nozzle.

Multi-port grains are a genuine design pain. The ports eventually regress into one another, slivers of unburnt fuel break loose and choke the nozzle, and you are left choosing between leaving a lot of fuel unburnt and carrying inert structural webs. Either way you fly dead weight. SpaceShipOne used a four-port HTPB grain for exactly this reason.

Paraffin sidesteps the problem through the entrainment mechanism in Section 4. Because droplets are torn mechanically off the melt layer rather than having to be vaporised, it regresses several times faster, and a single circular port can supply enough fuel at a sane grain length. That is the entire argument for paraffin, and Figure 7 is the evidence.

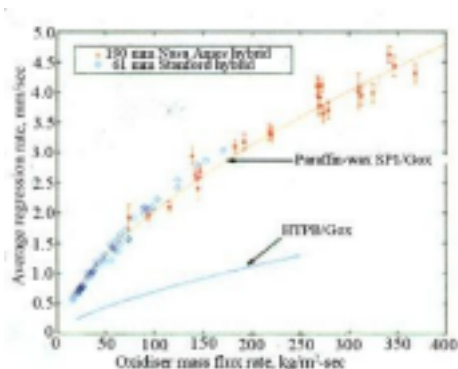


Figure 7 – Measured regression rate versus oxidiser mass flux for paraffin (SP-1) compared with HTPB, from Stanford / NASA Ames test motors. Data from Karabeyoglu, Cantwell & Altman via Newlands (2017).

Be aware of the honest counter-arguments:

- Not every group reproduces the published numbers. Several amateur teams have watched a wax grain simply melt and pour out of the nozzle. Formulation, additives, melting point and casting quality matter enormously, and candle wax is not one material.
- Wax is also mechanically weak. The grain has to survive casting shrinkage, transport, handling and axial acceleration in flight without cracking. Reinforcement — a cast-in liner, mesh or paper wrapping — and slow, careful casting to control voids are the normal countermeasures, and they are not optional.
- Voids matter more here than in a plastic hybrid. A cavity sets up a local circulation, the regression rate inside it rises, and the void grows rather than levelling out. In the worst case it reaches the liner and burns through the chamber wall. That makes it a Structures and manufacturing problem at least as much as a Propulsion one.
- And the fast regression rate is not free: it makes the O/F shift worse, not better. See Section 6. Fast-regressing fuels buy you geometry and charge you mixture-ratio stability.

6. Nitrous oxide: easy to use, easy to underestimate

First, the name. N_2O is dinitrogen monoxide. NO_2 is nitrogen dioxide, a toxic brown gas, and it is not a rocket propellant. Get this right in everything we publish.

At room temperature N_2O sits at roughly 50 bar of vapour pressure, and that is its single most attractive property: it pushes itself out of the tank. No helium bottle, no regulator, no pump. Everything below is the bill for

that convenience.

Blowdown. As liquid leaves the tank, some of what remains boils to fill the space. Boiling cools the tank, cooling drops the pressure, and so tank pressure — and with it oxidiser flow — falls throughout the burn. Modelling this self-pressurised, two-phase emptying properly is a real piece of work. It is also a very good first task for a new Propulsion member who enjoys numerics.

Two-phase flow at the injector. N_2O runs close to its critical point, so it flashes to vapour on its way through the injector. Incompressible orifice equations will over-predict your flow. If you want mass flow to any useful accuracy, you need a model that accounts for flashing.

Feed-system coupling. Hybrids are prone to low-frequency chugging when the pressure drop across the injector is too small compared with chamber pressure. The rule of thumb across student teams is to size the injector for about 20 % of chamber pressure.

It is not inert. N_2O is an energetic material in its own right. It can decompose exothermically, and hydrocarbon contamination plus a hot spot — adiabatic compression when a valve slams open on a dead-headed line, for instance — has killed people. The 2007 Scaled Composites test-stand explosion killed three engineers during a cold-flow test. Nobody was even burning anything. Clean plumbing, no oil or grease anywhere near the system, slow valve opening, remote operation and a real safety perimeter are not bureaucracy. They are the reason we get to keep doing this.

7. Where to read more

- **Newlands, R., "Introduction to hybrid design"**, plus the companion Aspirespace papers on nitrous oxide physics, hybrid safety and run-tank emptying. The most readable practical treatment for amateur teams, and the source of several figures here. Start here.
- **Karabeyoglu, Cantwell & Altman, "Development and testing of paraffin based hybrid rocket fuels", AIAA 2001-4503.** The entrainment theory behind paraffin's high regression rate.
- **Sutton & Biblarz, *Rocket Propulsion Elements*.** The general reference for nozzles, chamber sizing and performance parameters.
- **The EuRoC rules and design-report requirements.** Read these early. They constrain the design more than any equation in this document.