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The GREEN FOXFIRE Project: Sustainable Hybrid Propulsion for CubeSats Based on Paraffin/HTPB

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Abstract. The growing relevance of small satellites in space exploration, which in 2023 accounted for 97% of all spacecraft launched worldwide, requires addressing the challenges of propulsion miniaturization. To meet these needs, the GREEN FOXFIRE (Green Fuel and OXidizer For Innovative hybrid Rocket Engines) project investigates compact, efficient, and environmentally responsible hybrid systems, aiming to develop a sustainable hybrid rocket engine (HRE) capable of inserting a 24U CubeSat into Martian orbit from an Earth-orbit transfer. In this work, the performance of paraffin/HTPB fuel blends using gaseous oxygen as oxidizer was evaluated through a combination of numerical simulations and experimental ballistic tests. Paraffin offers high regression rates but limited mechanical strength, whereas HTPB improves structural integrity with lower combustion efficiency. Blended formulations (70/30, 50/50, 35/65, and 25/75 paraffin/HTPB ratios) were analyzed using NASA's Chemical Equilibrium with Applications (CEA) code and validated experimentally. Results confirmed that paraffin enhances regression rate and combustion efficiency, while HTPB contributes to mechanical robustness. Preliminary design activities also included a four-cluster thruster configuration with dual oxidizer tanks optimized for CubeSat mission requirements. Overall, the study demonstrates the feasibility of green hybrid propulsion as an enabling technology for interplanetary small-satellite missions, combining environmental sustainability with system scalability and performance.

Introduction

The rise of small satellites has reshaped space missions: from under 2% of total launch mass in 2013 to 97% of spacecraft by 2023 [1,2]. This miniaturization demands compact and efficient propulsion systems. Rocket engines are typically classified as solid, liquid, or hybrid. Solid motors are simple and reliable but lack controllability. Liquid engines offer precise thrust control but involve complex systems and hazardous propellants. Hybrid rocket engines (HRE) combine a solid fuel with a liquid or gaseous oxidizer, offering a compromise between safety, simplicity, and controllability.

Unlike traditional spacecrafts' mono- and bi-propellant systems that often rely on toxic substances like hydrazine [3], HRE can use greener propellants such as paraffin and nitrous oxide, reducing environmental and health risks [4].

Within this context, the GREEN FOXFIRE project proposes a hybrid propulsion system designed to insert a 24U CubeSat into Martian orbit. The mission profile was preliminarily

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analyzed to define performance requirements, leading to the development of a four-thruster configuration optimized for the spacecraft's mass, geometry, and delta-V needs [5].

To meet these demands with a sustainable approach, GREEN FOXFIRE investigates paraffin (P) and hydroxyl-terminated polybutadiene (HTPB) as solid fuels, paired with nitrous oxide (N_2O) and gaseous oxygen (O_2) as oxidizers. Paraffin offers high regression rates but lacks mechanical strength, while HTPB provides structural integrity with lower combustion efficiency [6,7]. Blending these fuels in various ratios (e.g., 70/30, 50/50, 35/65, 25/75) enables tailored performance characteristics suited to mission constraints. This integrated strategy supports the broader goal of enabling efficient, green propulsion for small-scale interplanetary exploration.

This work focuses on O_2 as oxidizer and integrates numerical simulations using NASA's Chemical Equilibrium with Applications (CEA) software and experimental ballistic testing to evaluate combustion behavior, regression rates, and performance metrics.

Fuel Preparation and Test Methodology

This study employs paraffin ($C_{28}H_{58}$) and HTPB ($C_{10}H_{15.4}O_{0.007}$) as solid fuels. HTPB is synthesized using poly bd® R45 V resin, with dioctyl adipate (DOA), toluene diisocyanate (TDI), and glycerol as additives to enhance flexibility and curing properties. Fuel blends were prepared with varying paraffin content, from 100% paraffin (100P) to 0% paraffin (0P), to assess the influence of composition on both material and combustion properties. All fuel formulations were tested using gaseous oxygen as oxidizer to evaluate the effects of fuel blending on combustion performance. Nitrous oxide will be introduced in future phases of the study.

Thermochemical analyses were performed using NASA's CEA software to predict the combustion behavior of the paraffin–HTPB blends. The simulations provided key performance parameters, including adiabatic flame temperature (T_{flame}), characteristic velocity (C*), and specific impulse (Isp). Simulations were conducted across a range of chamber pressures (50, 40, 30, 20, 10, and 5 bar) and oxidizer-to-fuel (O/F) ratios (0.5 to 7).

To experimentally evaluate the combustion performance of the paraffin–HTPB fuel blends, ballistic tests were conducted in the ASP Laboratory-scale hybrid rocket motor (Fig. 1). The setup included a thrust stand-mounted motor, an oxidizer feed line with a stainless-steel axial flow injector, a pyrotechnic igniter and a NI lab view based data acquisition system. The combustion chamber measures 240 mm in length and 80 mm in diameter and is equipped with a convergent-divergent nozzle featuring a 12 mm throat and semi-angles of 45° (convergent) and 13° (divergent).

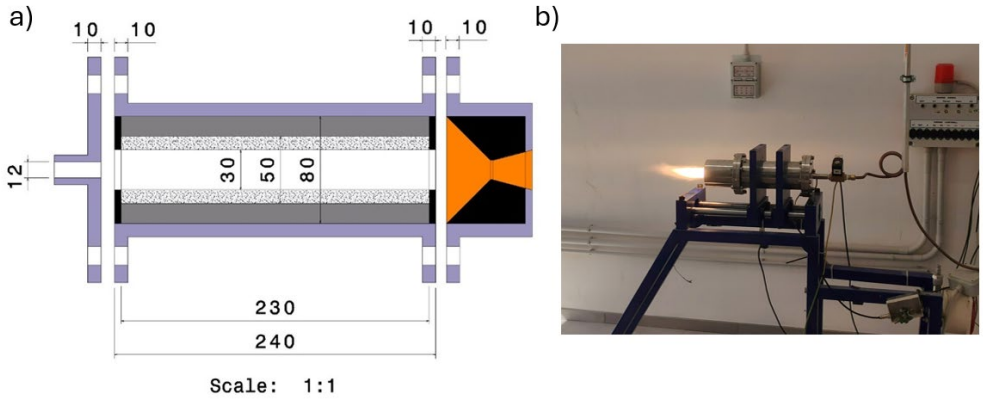


Fig. 1. HRE at the School of Aerospace Engineering: (a) motor schematic; (b) operational phase.

Each firing test lasted 5 or 10 seconds, with oxidizer flow regulated by a pressure controller and solenoid valve. After each test, the fuel grain was extracted and weighed to determine mass loss.

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The regression rate ($\dot{\mathbf{r}}$) was calculated using the weight loss method, based on the difference between initial and final fuel mass ($\mathbf{m_b}$), burn duration ($\mathbf{t_b}$), and port geometry using port area diameter before ignition ($\mathbf{d_{ig}}$) and after burning ($\mathbf{d_b}$), using the following equations [8]:

$$\dot{r} = \frac{d_b - d_{ig}}{2t_b} \tag{1}$$

$$d_b = \sqrt{d_{ig}^2 + \frac{m_b}{\frac{\pi}{4}\rho_f l_f}} \tag{2}$$

$$G_{ox} = \frac{\dot{m}_{ox}}{\frac{\pi}{4}\left(\frac{d_b + d_{ig}}{2}\right)^2} \tag{3}$$

ρ_f and l_f refer to the fuel density and grain length, respectively, while $\dot{m}_{ox}$ and G_{ox} denote the oxidizer mass flow and oxidizer mass flux rate.

Theoretical Results

The CEA analyses were performed using five fuel combinations (100P, 70P, 35P, 25P, 100HTPB) and six pressures (from 5 to 50 bar), across O/F ratios ranging from 0.5 to 7. Fig. 2 presents the adiabatic flame temperature for the investigated pressures as a function of O/F ratio. All fuels show low adiabatic flame temperatures at low O/F (<2) due to insufficient oxidizer and incomplete combustion.

Maximum temperatures (of order of 2900 K) are observed between O/F 2–4. This range is coherent with stoichiometric ratios found in literature that are 3.4 for O_2/P combustion [9] and 2.95 for O_2/HTPB combustion [10], respectively, where combustion is nearly complete. Beyond this range, excess oxidizer lowers flame temperature. As shown by the temperature trend (T25P > T35P > T70P > T100P), fuels with higher hydrogen content exhibit lower flame temperatures at low and mid O/F ratios, indicating a greater oxidizer demand for complete combustion.

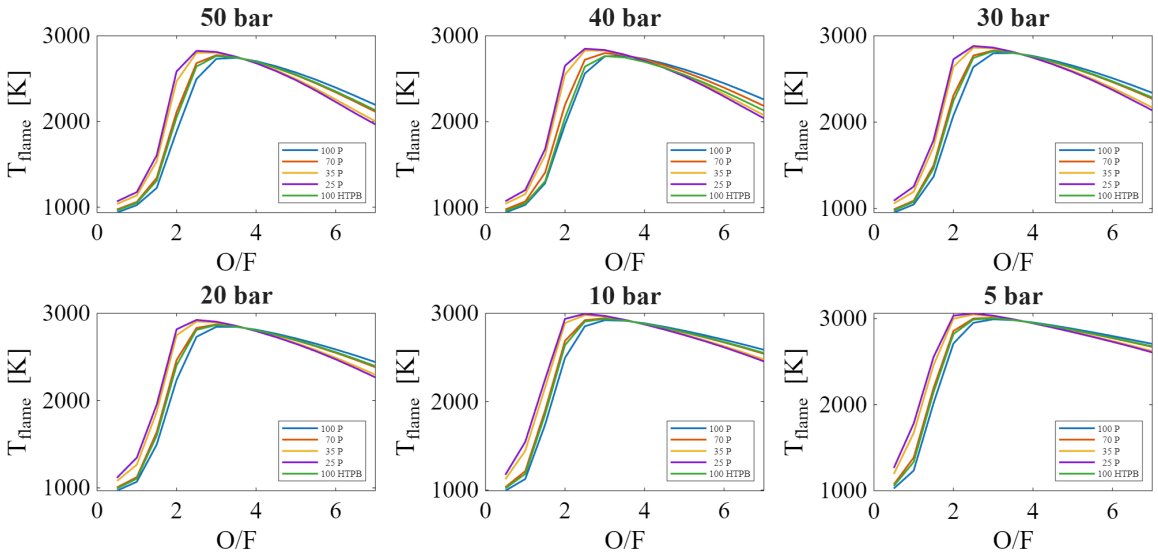


Fig. 2. CEA adiabatic flame temperature, for investigated fuels, as a function of O/F for various pressures.

Between 100P and 100HTPB, the latter exhibits higher flame temperatures at low to mid O/F due to its lower hydrogen content and better reactivity with limited oxidizer. At high O/F, the temperature trend reverses: T100P > T100HTPB > T70P > T35P > T25P.

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Regarding characteristic velocity (C*, plots in Fig. 3), low O/F ratios yield lower values due to incomplete combustion. The optimal range for C* (1700 m/s for 25P to 1900 m/s for 100P) is O/F 2–2.5. Across all O/F values, 100P shows higher C* than 100HTPB (1800 m/s).

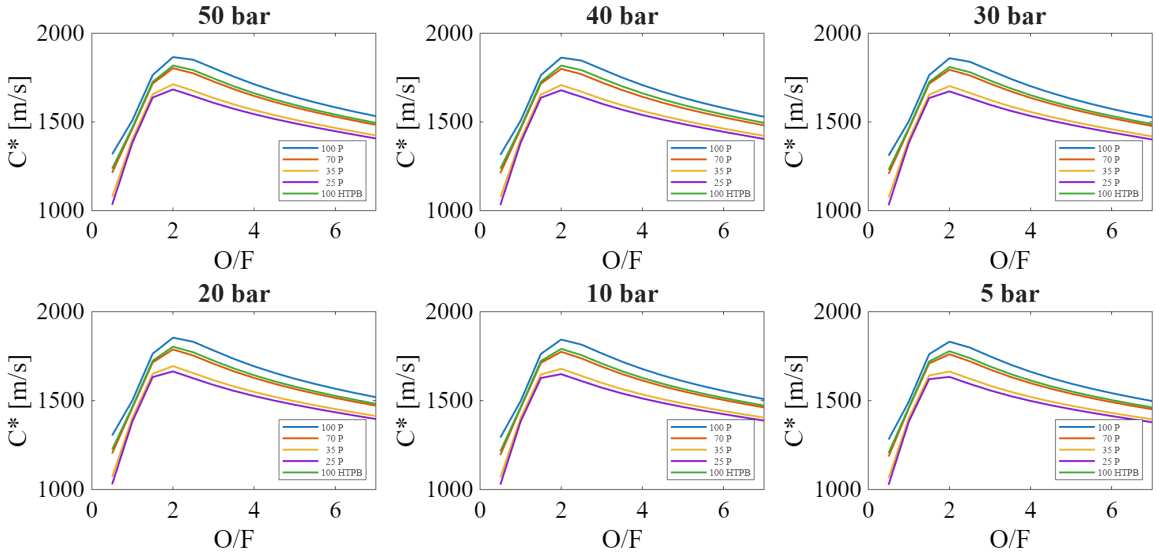


Fig. 3. CEA characteristic velocity, for investigated fuels, as a function of O/F for various pressures.

Specific impulse follows the C* trend, being lower at low O/F ratios due to incomplete combustion, peaking near stoichiometric conditions (O/F 2–3), and decreasing with excess oxidizer. Fig. 4 reports the peak specific impulse values for various propellants as a function of chamber pressure. The plot highlights how Isp decreases with lower pressure, as reduced pressure promotes product separation, thereby diminishing both thrust and specific thrust.

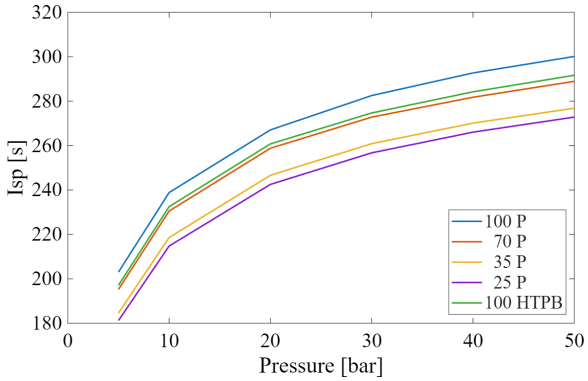


Fig. 4. CEA specific impulse, for investigated fuels, as a function pressure at stoichiometric O/F.

Experimental Results

The ballistic tests (Table 1) were conducted at the ASP Laboratory (Fig. 1). Pure paraffin fuel exhibited the highest regression rate (0.9 mm/s) at the lowest oxidizer mass flux (25.25 kg/m²·s), with a final port diameter of 47.8 mm. In contrast, blended fuels showed reduced regression rates, clustering around 0.3–0.4 mm/s despite varying HTPB content. The 25P and 0P formulations reached 0.4 mm/s, while 35P, 50P, and 70P blends maintained 0.3 mm/s across different mass fluxes. These results indicate a general decline in regression rate with increasing oxidizer mass flux and highlight the trade-off introduced by HTPB: although it lowers regression rates, it enhances structural integrity.

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Table 1. Data from ballistic testing.

Fuel	Gox [kg/(m^2·s)]	O_2 mass [g]	Grain initial mass [g]	Grain final mass [g]	ṙ [mm/s]	Final port diameter [mm]	O/F
100 P	25.25	300	820	600	0.9	47.8	1.4
70 P	35.40	140	780	745	0.3	33.5	4.0
50 P	25.36	100	800	766	0.3	33.4	2.9
35 P	30.52	120	812	779	0.3	33.3	3.6
25 P	30.24	120	829	793	0.4	33.6	3.3
0 P	27.56	110	743	708	0.4	33.8	3.1

The motor firing sequence included ramp-up, steady-state, and cut-off phases, as illustrated in Fig. 5. After ignition, a rapid pressure spike was followed by combustion stabilization around 0.5 s. During steady-state operation, 100P fuel delivered the highest performance, reaching ~3.5 bar chamber pressure and 3500–4000 g thrust. Blends like 25P and 35P sustained ~3.0 bar and ~2500–3000 g thrust, while 50P and 70P showed intermediate and stable behavior, respectively.

The 0P formulation matched or exceeded the 50P blend, achieving ~3.5 bar and ~5000 g thrust. All fuels exhibited a sharp drop in pressure and thrust during the cut-off phase, marking complete flameout.

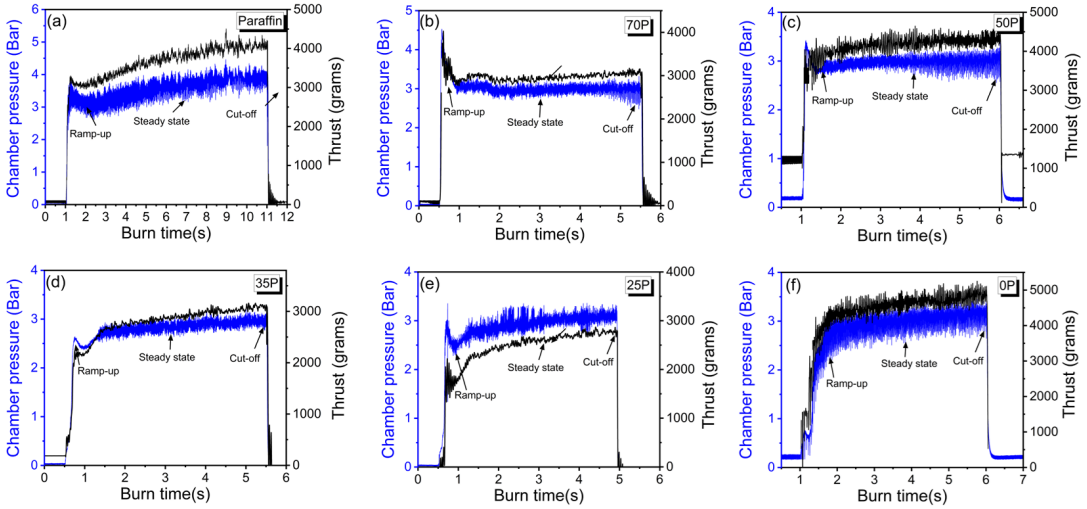


Fig. 5. Combustion chamber pressure and thrust profile for 100P (a), 70P (b), 50P (c), 35P (d), 25P (e), and 0P (f) combustion with gaseous oxygen.

Conclusion

The GREEN FOXFIRE project aims to demonstrate the feasibility of sustainable hybrid propulsion for small satellite missions, specifically targeting Mars orbit insertion for a 24U CubeSat. Through a combination of numerical simulations and ballistic testing, paraffin–HTPB fuel blends paired with gaseous oxygen were shown to offer a viable balance between combustion efficiency and structural integrity. Pure paraffin achieved the highest regression rates (0.9 mm/s), while HTPB contributed to mechanical robustness. During steady-state operation, thrust levels were ~3500–4000 g for 100P, ~3000 g for 70P and 50P, ~2500–3000 g for 35P and for 25P, and ~5000 g for 0P. Performance metrics such as adiabatic flame temperature, characteristic velocity, and specific impulse confirmed optimal combustion near stoichiometric O/F ratios, with pressure-dependent enhancements. The successful integration of a multi-thruster configuration and oxidizer injection system will support the potential of this green hybrid architecture for future interplanetary missions.

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