Review of Electric Propulsion Technologies with Emphasis on Hall Effect Thruster for Satellite Operations

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Abstract - *The exponential growth of small satellite deployments and the increasing density of orbital debris necessitate compact, efficient, and sustainable propulsion systems capable of executing precise maneuvers and extended operational lifetimes. While traditional chemical propulsion is limited by severe size and efficiency constraints, scaling down complex electric propulsion (EP) systems for power-constrained micro-platforms introduces significant engineering challenges. This paper presents a comprehensive review and comparative analysis of five leading electric propulsion technologies: Pulsed Plasma Thrusters (PPTs), Electrospray Thrusters, Gridded Ion Engines, Vacuum-Arc Thrusters (VATs), and Hall-Effect Thrusters (HETs). These systems are evaluated across critical mission parameters, including thrust-to-power ratio, specific impulse, system complexity, and flight heritage. The analysis demonstrates that while technologies like PPTs and Electrosprays serve niche ultra-low-power roles, Hall-Effect Thrusters provide the optimal balance of scalable thrust, efficiency, and integration feasibility. Ultimately, this study establishes HETs as the most viable baseline technology for modular small satellite propulsion systems tasked with orbit maintenance, collision avoidance, and decommissioning.*

Keywords - *Electric Propulsion, Hall-Effect Thrusters (HET), Small Satellite Propulsion, Micro-thrusters, Orbital Maneuvering, Propulsion Systems Review.*

I. INTRODUCTION

The rapid expansion of satellite technology and the deployment of vast small-satellite constellations have created an urgent demand for efficient, low-mass, and sustainable in-space propulsion systems. Traditional chemical propulsion, while historically effective, is fundamentally limited by high propellant consumption, restrictive mass fractions, and brief operational lifespans, rendering it increasingly unsuitable for long-term micro-satellite operations.

Electric propulsion (EP), which utilizes electrical energy to accelerate charged particles, offers a significantly higher specific impulse and greater propellant efficiency. This makes EP the premier choice for critical orbital operations, including station-keeping, orbit raising, and fine attitude control. However, selecting the appropriate EP technology for a small satellite involves navigating strict limits on available power, physical volume, and allowable system complexity.

This paper provides a systematic review of the electric propulsion landscape for small satellites. It evaluates the operational mechanisms, performance metrics, and flight heritage of five primary technologies: Pulsed Plasma Thrusters (PPTs), Electrospray Thrusters, Gridded Ion Engines, Vacuum-Arc Thrusters (VATs), and Hall-Effect Thrusters (HETs). By conducting a comparative analysis of these systems, this study aims to identify the most adaptable and efficient propulsion architecture for power-constrained spacecraft. Specifically, it highlights how Hall-Effect Thrusters stand out as a highly versatile option, delivering the continuous, controllable thrust required to meet the evolving maneuverability and debris mitigation needs of modern satellite missions.

II. LITERATURE REVIEW

Electric propulsion (EP) has steadily emerged as the enabling technology for small satellite missions requiring efficient orbit maintenance, attitude control, and debris avoidance. Early studies, such as those by Jahn [1], established the theoretical foundations of EP, demonstrating its superior specific impulse compared to chemical propulsion. Sutton and Biblarz [2] extended this by benchmarking electric systems against conventional chemical alternatives, revealing their advantages in lifetime and propellant efficiency for deep-space and long-duration missions.

Among EP technologies, **Pulsed Plasma Thrusters (PPTs)** were among the first to fly on small spacecraft, with Mueller [3] documenting their successful integration on early CubeSat missions. PPTs are valued for simplicity and robustness but suffer from low efficiency and limited continuous thrust capability. **Electrospray thrusters**, extensively studied by Lozano and colleagues at MIT [4], provide extremely fine thrust control with low power consumption, making them attractive for precision maneuvers, though emitter erosion remains a key limitation.

Gridded ion engines, with their high specific impulse and flight heritage on missions such as *DART* and *Deep Space 1*, have been described comprehensively by Goebel and Katz [5]. However, their large power and volume requirements hinder adoption in CubeSats. **Vacuum Arc Thrusters (VATs)**, explored in works by Anders and Andersson [6], represent a compact alternative, but cathode erosion and lack of extensive flight heritage keep their TRL low.

Finally, **Hall Effect Thrusters (HETs)** have gained prominence as a balanced solution, combining moderate thrust, high efficiency, and scalability. Jorns et al. [7] and Hofer [8] demonstrated their adaptability to CubeSat platforms, while Lev [9] investigated cylindrical geometries for miniaturization. NASA Glenn's work on magnetic shielding (Sovey [10]) further extended HET lifetimes by mitigating wall erosion, strengthening their suitability for operational small satellite constellations.

Despite this progress, most comparative studies treat these propulsion systems in isolation, with limited emphasis on **scalability, modularity, and integration into power-constrained spacecraft**. This paper addresses that gap by providing a unified review and comparative analysis of major EP technologies, with a focus on why Hall Effect Thrusters stand out for modular small satellite propulsion.

III. COMPARATIVE ANALYSIS

A systematic comparison of five leading electric propulsion technologies, Pulsed Plasma Thrusters (PPTs), Electrospray Thrusters, Gridded Ion Engines, Hall-Effect Thrusters (HETs), and Vacuum-Arc Thrusters (VATs), was conducted to evaluate their suitability for small satellite maneuvering. Each technology differs significantly in thrust capability, efficiency, power consumption, complexity, and heritage. Table 1 provides a consolidated overview across major performance parameters.

Pulsed Plasma Thrusters (PPT)

Description and Working Principle:
Pulsed Plasma Thrusters operate by ablating a solid polymer propellant bar made of polytetrafluoroethylene (PTFE, commonly known as Teflon) through rapid electrical discharges. Each discharge pulse forms a plasma sheet from the ablated propellant material, which is accelerated primarily by the self-induced Lorentz force (J x B) generated between current-carrying electrodes and their magnetic fields. The system fires these discrete impulse bits at repetition rates that can be controlled from a few pulses per second to thousands. Core components include the PTFE bar, a spark plug igniter, paired electrodes, a pulse-forming network (capacitors and fast electrical switches), and a compact power processing unit (PPU).

Typical Performance in a Micro/Small Satellite Envelope:

Thrust produced is about 10 to 800 μN per thruster head and is scalable by clustering multiple units. Specific Impulse (Isp) is approximately 600–1200 seconds, with modern designs occasionally exceeding this. Average power consumed is between 1–10 W, with pulsed high-peak currents and duty cycle limitations. Flight units typically achieve about 5–10% efficiency, optimal for ultra-low-power applications.

Current being employed by:
NASA's EO-1 mission successfully flew PPTs to provide high-precision attitude control, demonstrating efficient torque generation as an alternative to reaction wheels, while confirming manageable thruster plume and electromagnetic interference on orbit. FalconSAT-3 equipped with four Busek micro-PPTs set a precedent for low size, weight, and power (SWaP) pulsed systems on small satellites. Modern PPT efforts, such as the PPTCUP and mini-PPT programs, target orbit-keeping for CubeSats with advances in electronics and packaging.

Technological Advantage:
PPTs are the simplest form of electric propulsion that produce real delta-V and precise attitude control with minimal power and mass impact. Their modular, pulsed nature suits power-starved, mass-constrained spacecraft, making them excellent candidates for micro-propulsion solutions on small satellites.

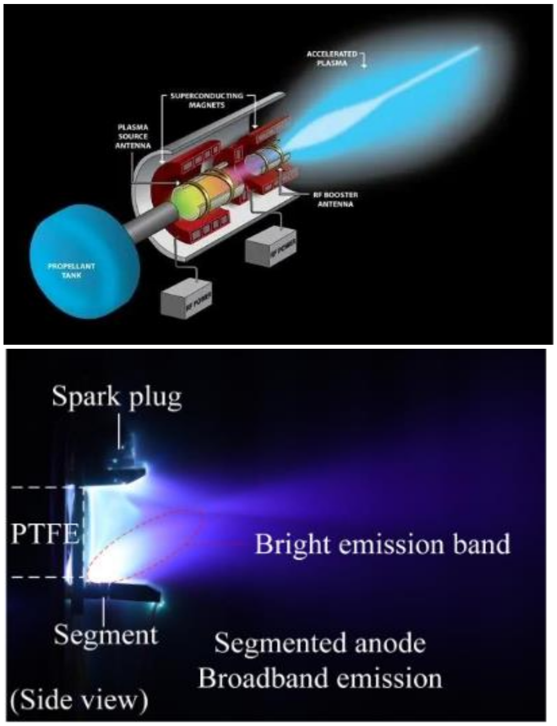


Fig. 4.2 Components and Operation of PPT

Electrospray Thrusters (Colloid/FEEP)

Description and Working Principle: Electrospray thrusters operate by forming nanoscale Taylor cones at sharp emitter tips or elongated slits where high electric fields extract ions or charged liquid droplets from ionic liquids or liquid metals (Field Emission Electric Propulsion-FEEP). These charged particles are electrostatically accelerated to produce thrust.

Typical Performance in a Micro/Small Satellite Envelope:

Thrust produced is from micro-Newton up to sub-milli-Newton levels, depending on the array size. Specific Impulse (Isp) ranges from 1000 to 6000 seconds and is tunable for mission requirements. Average power consumed is around sub-watt to a few watts, with excellent precision and throttling capability. The challenges faced include emitter erosion, emission current stability, contamination control, and complex high-voltage packaging.

Current being employed by: NASA's LISA Pathfinder mission employed Busek colloid micro-Newton thrusters for drag-free satellite control, setting the standard for thrust precision in space. ENPULSION's FEEP thrusters hold an extensive in-orbit record with missions performing geostationary orbit transfer and station-keeping. Accion Systems' TILE electrospray thrusters have been demonstrated on CubeSat rideshare missions, showcasing increasing commercial adoption.

Technological Advantage: Electrospray thrusters deliver extremely fine thrust control at ultra-low power, perfect for precision station-keeping, formation flying, or platforms requiring drag compensation. They are highly advantageous when mission success depends on precise maneuvering within tight power budgets.

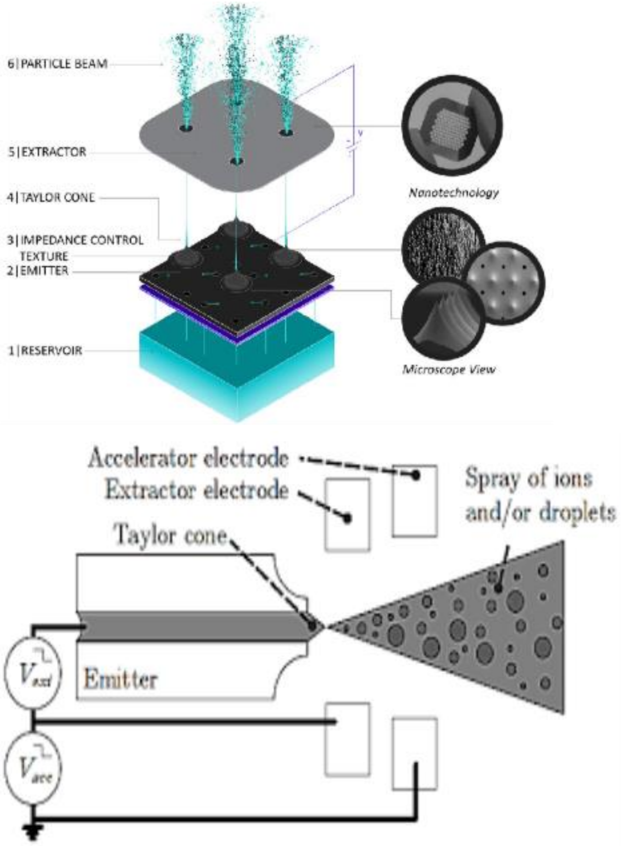


Fig. 4.3 Components and Operation of Electrospray Thruster

4.6.3 Gridded Ion Thrusters

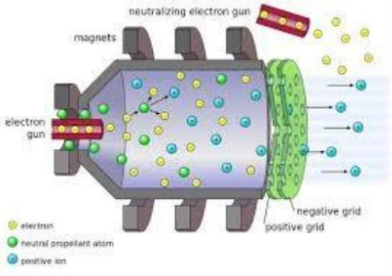
Description and Working Principle: Gridded ion engines function by ionizing a noble gas propellant, typically xenon, within a discharge chamber. Ionization may be accomplished by hot-cathode or radio frequency (RF) techniques. Positively charged ions are accelerated through a series of electrostatic grids, achieving exhaust velocities on the order of tens of kilometers per second. A neutralizer emits electrons into the ion beam to avoid spacecraft charging, with magnetic fields confining electrons to enhance ionization efficiency.

Typical Performance:

Thrust produced is approximately 10 mN to over 250 mN, with systems scaling from sub-kilowatt to multi-kilowatt power levels. Specific Impulse (Isp) ranges broadly from 2000 up to 10,000+ seconds, with mission-selectable modes. Power range is typically between 0.5 and 7 kW or more, requiring complex power processing and xenon feed systems.

Currently being employed by:
NASA's Deep Space-1 demonstrated NSTAR ion thrusters operating over 10,000 hours in flight. The Dawn mission used NSTAR derived thrusters for conducting extended operations around Vesta and Ceres. The European Space Agency's GOCE satellite utilized QinetiQ's T5 thruster in drag-free control applications with a record operational duration surpassing 36,000 hours. The BepiColombo mission employs advanced QinetiQ T6 thrusters for Mercury orbit insertion. NASA's NEXT-C ion thruster has been flight qualified and deployed on missions such as the DART asteroid impactor.

Technological Advantage:
Gridded ion engines represent the pinnacle of efficiency and durability for missions requiring large total impulse and deep-space delta-V. Despite their power and complexity making them less suitable for very small satellites, they provide benchmark technology for propulsion performance and valuable data for erosion and plume modeling.



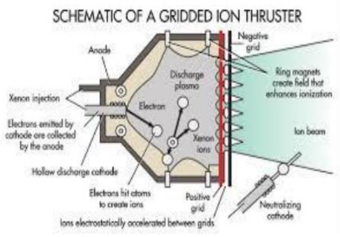


Fig. 4.4 Components and Operation of Gridded Ion Thruster

4.6.4 Hall-Effect Thrusters (HET)

Description and Working Principle:
Hall-effect thrusters feature a cylindrical or annular acceleration channel where electrons are magnetically trapped in an azimuthal current and an axial electric field accelerates ions through E x B effects. A cathode provides electrons that ionize the propellant gas and neutralize the outgoing ion beam plume. Hall thrusters offer simpler, gridless ion acceleration delivering higher thrust-to-power ratios but slightly lower specific impulse (Isp) than gridded ion engines.

Typical Performance:

Thrust produced is about 5 mN up to 300 mN for single channel units. Specific Impulse (Isp) is approximately 1500 to 3000 seconds with xenon, with somewhat lower performance than when using krypton propellant. Power ranges from 100-200 W scaling upward to tens of kilowatts, allowing broad system scalability.

Currently being employed by:
The European SMART-1 lunar mission flew the PPS-1350-G Hall thruster end-to-end for moon transfer. NASA's Psyche mission applies SPT-140 Hall thrusters for solar-electric propulsion cruise phases. SpaceX Starlink satellites employ mass-produced krypton Hall thrusters across their constellation for orbit raising and maintenance, evidencing high reliability and industrial scale production.

Technological Advantage:
HETs deliver an excellent balance of thrust, efficiency, and scalability for small satellite missions. Their mature technology status, ease of integration in modular arrays, and capability for meaningful orbit changes make them ideal for projects needing higher thrust than PPTs while managing medium power budgets.

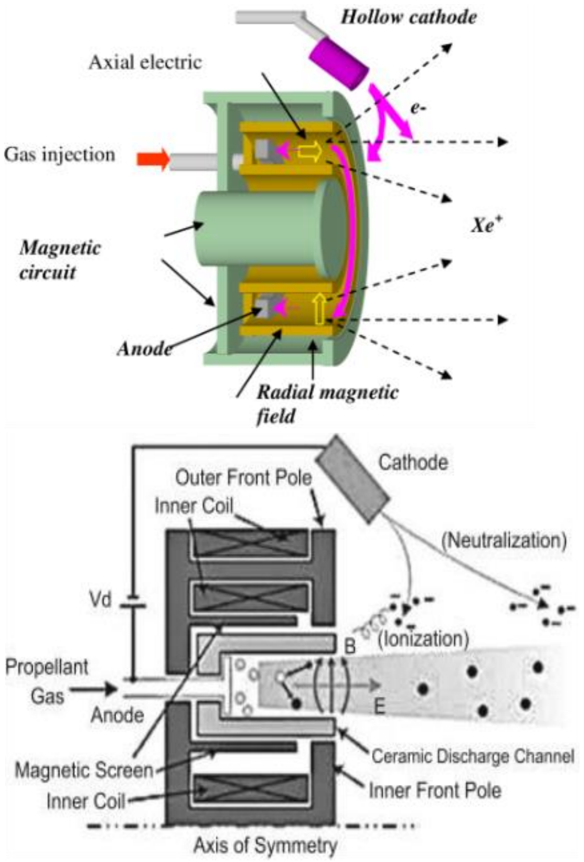


Fig. 4.6 Components and Operation of HET

4.6.5 Vacuum-Arc Thrusters (VAT)

Description and Working Principle: Vacuum-Arc Thrusters operate by maintaining a cathodic vacuum arc that vaporizes a solid metallic cathode (commonly titanium or similar metals) into dense plasma. This plasma, created in short, high-current pulses, is ejected and accelerated as discrete impulse bits, similar to PPTs but using solid metal cathode material instead of polymer propellant.

Typical Performance in a Micro/Small Satellite Envelope:

Thrust output is typically in the micro-Newton millisecond range, with also the ability to scale total thrust by arraying multiple µCAT units. It consumes very low average power making it suitable for ultra-compact propulsion needs.

Currently being employed by: BRICSat-P, flown by the Naval Academy and GWU, implemented a multi-head µCAT system for spacecraft detumbling and attitude control missions, verifying initial flight operations. Research demonstrates evolving power processing and array operation to support CubeSat-scale propulsion, with technology readiness levels progressing through TRL-6 to TRL-7.

Technological Advantage: VATs offer exceptional packaging efficiency and simplicity using solid-propellant logistics. Their ultra-compact size and pulsed operation make them ideal for debris remediation buses, emergency in-space delta V, and momentum management on constrained spacecraft, serving as complementary actuators to a main propulsion system.

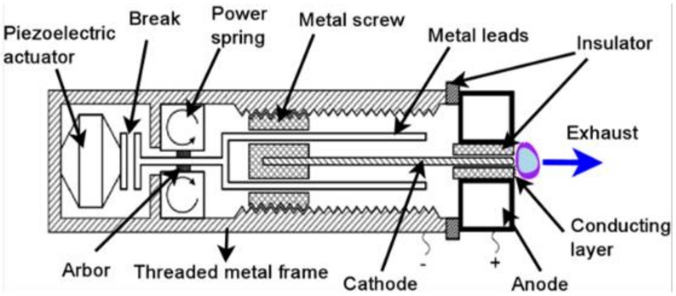


Fig. 4.7 Components and Operation of VAT

Table 1: Comparative Summary of Electric Propulsion Technologies for Small Satellites

Parameter	**Pulsed Plasma Thrusters (PPT)**	**Electrospray Thrusters**	**Gridded Ion Engines**	**Hall-Effect Thrusters (HET)**	**Vacuum-Arc Thrusters (VAT)**
Thrust Range	10–800 µN (clusterable)	µN to sub-mN	10–250+ mN	5–300 mN (scalable)	µN-ms impulse bits (arrays)
Specific Impulse (Isp)	600–1200 s	1000–6000 s	2000–10,000+ s	1500–3000+ s	Variable impulse bits
Power Requirement	1–10 W average (pulsed peaks)	Sub-watt to few watts	0.5–7+ kW	100 W – multi-kW	Very low average
System Complexity	Very low	Moderate (emitters, HV)	High (grids, feed)	Moderate to high	Low

Mass and Volume	Very compact	Low mass, micro-scale	Higher (bulky)	Moderate	Very compact
Thrust-to-Power Ratio	Moderate	Low to moderate	Moderate	High	Low
Flight Heritage	EO-1, FalconSAT-3	LISA Pathfinder, GEO	Deep Space-1, Dawn	SMART-1, Starlink, Psyche	BRICSat-P CubeSat
Operational Lifetime	Moderate (propellant limited)	High (erosion issues)	Very high (>10,000 h)	High (improved w/ shielding)	Moderate (erosion-limited)
Suitability for Small Sats	Excellent for ultra-small	Excellent for precision	Limited (power/mass)	Excellent (scalable)	Good for attitude/ detumble

IV. DISCUSSIONS

The comparative analysis reveals that while each propulsion technology offers unique advantages, their utility for **power- and mass-constrained satellite missions** varies widely:

Pulsed Plasma Thrusters (PPTs): Extremely simple and robust, PPTs are best suited for very small satellites requiring ultra-low power operation. Their pulsed operation enables precise impulse control, but their **low efficiency** and limited continuous thrust restrict their use to attitude control and small orbit maintenance tasks.

Electrospray Thrusters: These provide **exceptional precision** at ultra-low power levels, making them ideal for drag compensation, formation flying, and nanosatellite control. However, their **limited thrust output** and emitter degradation hinder broader applications where substantial delta-V is required.

Gridded Ion Engines: Ion engines deliver the **highest specific impulse and efficiency**, making them unparalleled for deep-space, high-delta-V missions. Nevertheless, their **large power and volume requirements** make them impractical for CubeSats and small satellites, despite their extensive heritage in flagship missions.

Vacuum-Arc Thrusters (VATs): Ultra-compact and simple in design, VATs are useful for **attitude control and detumbling** in small satellites. However, cathode erosion and low total thrust capability limit their adoption as primary propulsion systems.

Hall-Effect Thrusters (HETs): Offering a **balanced compromise** between thrust, efficiency, and power consumption, HETs have demonstrated scalability from micro-thrusters (~100 W) to high-power multi-kilowatt units. Their adoption in **operational constellations like Starlink** proves industrial readiness, while research into **magnetic shielding and miniaturization** enhances their reliability for small spacecraft. HETs are therefore uniquely suited for missions requiring **orbit raising, station-keeping, and collision avoidance** under constrained power budgets.

V. KEY FINDINGS

PPTs and Electrosprays excel in ultra-low-power niches but lack sufficient thrust for large maneuvers.

Ion engines dominate in high-delta-V deep space missions but are impractical for small satellites.

VATs remain emerging, with roles limited to **complementary control systems**.

HETs emerge as the **optimal choice**, balancing thrust, efficiency, and system integration feasibility, while maintaining proven flight heritage.

Thus, Hall-Effect Thrusters are validated as the **most suitable propulsion system** for modular small satellite propulsion, enabling scalable designs that align with future constellations and debris-mitigation missions.

VI. FUTURE DIRECTION

While Hall-Effect Thrusters (HETs) present the most balanced option for small satellite propulsion, several technological advancements are still required to maximize their potential:

Miniaturization of HETs: Ongoing research into sub-100 W HETs is critical for CubeSats and nanosatellites. Improved power processing units (PPUs) and micro-fabricated magnetic coils can enhance integration into ultra-compact platforms.

Alternative Propellants: Current reliance on xenon, though effective, is costly and logistically challenging. Propellants such as krypton, iodine, and even atmospheric-breathing concepts in very low Earth orbit (VLEO) are being actively investigated to reduce cost and extend mission lifetimes.

Lifetime Enhancement: Cathode erosion and thermal loading remain limiting factors for long-duration missions. Advanced magnetic shielding, novel cathode designs, and new thermal materials can extend operational lifetimes to match ambitious satellite constellations.

System Integration: Modular HET clusters, when paired with intelligent power management and adaptive thrust control algorithms, can provide reconfigurable propulsion for multi-role missions such as station-keeping, collision avoidance, and orbit-raising.

Hybrid Systems: Combining HETs with ultra-low power systems like Electrospray thrusters may enable fine attitude control without sacrificing overall maneuverability. Such hybrid configurations could become the baseline for next-generation multi-satellite constellations.

VII. CONCLUSION

This review has provided a comparative assessment of five major electric propulsion technologies—Pulsed Plasma Thrusters, Electrospray Thrusters, Gridded Ion Engines, Hall-Effect Thrusters, and Vacuum-Arc Thrusters—focusing on their applicability to small satellite missions.

The analysis highlights that while PPTs and Electrosprays are highly efficient at ultra-low power and precision tasks, they fall short for large-scale orbit changes. Gridded Ion Engines, though extremely efficient and flight-proven, are unsuitable for power- and volume-limited platforms. VATs remain emerging with complementary but limited primary capabilities.

In contrast, Hall-Effect Thrusters strike a unique balance of **thrust, efficiency, and scalability**, making them the most practical propulsion choice for modular and power-constrained satellites. Their extensive flight heritage, adaptability to new propellants, and ongoing advancements in miniaturization and lifetime management firmly establish them as the **propulsion technology of choice** for the future of small satellite operations.

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