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Survey and Performance Evaluation of Small-Satellite Propulsion Technologies

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The growing interest in small satellites (smallsats) is primarily a function of their affordability and versatility across a wide range of space mission applications. For these reasons, smallsats have found valuable applications in government, industry, and academic settings. The continued advancement of smallsats depends on the ability of the aerospace industry to supply affordable, reliable, and efficient miniaturized spacecraft thrusters. Choosing a suitable propulsion system for a smallsat mission involves tradeoffs between performance, cost, and reliability. This study compares the advertised performance of existing chemical, cold gas, and electric propulsion systems across two representative smallsat missions with the goal of providing mission-enabling information to the smallsat research community. Results show that electric propulsion systems are the top performers for both missions. The required wet mass for electrospray thrusters and pulsed plasma devices demonstrated low sensitivity to increasing orbit lifetime, increasing less than 0.5 kg over 15+ year increases in orbit lifetime, making them the top-performing systems in a low-impulse long-duration mission. Because of their characteristically high specific impulse, gridded ion thrusters emerged as the top-performing systems in a high-impulse interplanetary mission with delivered mass capability decreasing less than 25 kg for a delta-V increase of 2000 m/s.

I. Introduction

INCREASED affordability of small satellites (smallsats) has redefined the major players for this class of missions. Primary applications include global communication, navigation, Earth observation, remote sensing, and scientific missions. Although civil and military operator demand still plays a major role in the market for smallsats, commercial operators are expected to encompass over 70% of nano/microsatellites launched in the next five years [1]. This is a notable shift from the historical market distribution, where only civil, military, and a small number of the largest commercial entities could afford to design, manufacture, launch, and operate spacecraft. Beyond the commercial sector, the economic benefits of smallsats also make them viable investments for universities and research institutions.

Although classification cutoffs differ across the industry, "smallsat" generally refers to a spacecraft with a total mass under 500 kg. Smallsats comprised several subsystems, including payload, communication and data handling, power, and mobility (propulsion and attitude control). The propulsion subsystem is a defining characteristic of smallsats, providing the primary means of mobility as well as mission-specific operations, such as orbit changing and station keeping. Until recently, smallsat propulsion options were generally categorized into low-cost/low-performing and high-cost/high-performing systems [2]. SpaceWorks 2018 Nano/Microsatellite Market Forecast predicts that up to 2600 nano/microsatellites will be launched over the next five years [1]. The strong market demand for a low-cost/high-performing, reliable smallsat propulsion system sparked the rapid advancement of commercial smallsat propulsion options. Smallsat designers now have the opportunity to choose from a variety of commercial-off-the-shelf (COTS) propulsion options, which are broadly categorized into chemical, cold gas, and electric propulsion systems.

This paper provides an overview and comparison of the propulsion systems that are available for smallsat missions in terms of the wet mass required across increasing orbit lifetimes and their delivered mass capability for a given delta-V impulse. Delivered mass refers to the spacecraft's total mass minus the mass of the propulsion system and propellant. Some of the propulsion technologies considered in this survey have flown as the primary propulsion system on smallsats and/or as secondary propulsion on larger satellites, whereas others remain in the development phase. A direct comparison of chemical, cold gas, and electric propulsion technologies using only performance factors, such as thrust and specific impulse, is not a straightforward process, given the various strengths and weaknesses of these technologies across different mission requirements and limitations. To maximize the usefulness of the comparisons presented in this paper, two representative mission profiles are defined and trade studies are performed using commercially available performance data from smallsat propulsion-system manufacturers. Nominal thrust output, propulsion-system dry mass, and specific impulse were the primary parameters of interest in the trade studies.

II. Methodology

This work aimed to identify which smallsat propulsion systems are best suited for different mission requirements, namely, delivered mass to orbit and propulsion-system wet mass required, using discrete thruster performance data. For the analyses described in this paper, "small satellite propulsion" systems are defined as propulsion systems that require less than or equal to 200 W of power during nominal thruster operations. Performance data were collected for 21 propulsion systems: five chemical propulsion systems, two cold gas systems, and 14 electric propulsion systems. Performance data for these 21 systems were used to conduct trade studies across two baseline missions. Results are presented for the top 10 highest-performing systems in each mission scenario.

NASA's General Mission Analysis Tool (GMAT) was used in performing the trade study analyses. Licensed under the NASA Open Source Agreement, GMAT is used for design, optimization, and navigation in flight trajectories ranging from low Earth orbit (LEO)

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to deep space [3]. Analysts model in GMAT by first defining physical resources and analysis model resources. Physical resources include elements, such as the spacecraft, thruster, tank, trajectory, and burn characteristics. Analysis model resources include integrators, estimators, and optimizers. For the trade studies discussed in the current work, GMAT was used in the velocity–normal–binormal (VNB) frame to simulate the constant firing of a thruster in the x direction (direction of the velocity vector). The epoch was set to 18 June 2018. An eighth-order nine-stage Runge–Kutta integrator was selected. In addition to the analysis settings described previously, GMAT required information on each propulsion system's dry mass and performance in terms of nominal thrust output and specific impulse. A literature review of COTS and laboratory model smallsat propulsion systems was performed to collect these system characteristics [4–25]. The propulsion systems selected for the analysis are a selection of those systems with the most complete data sets publicly available at the time of the literature review.

Continuous thrusting was assumed primarily because start-up and shutdown transient data for the propulsion systems considered in the current work are not readily available. Furthermore, even if these transients were considered in the GMAT analyses, the effects would be minimal and not significantly affect the results of the comparison, which show clear winners in different technology categories exceeding margin of error. For instance, incorporating start-up/shutdown transients in the NASA Space Launch System trajectory modeling for the RL 10 engines at a high level of thrust for the upper stage had the effect of a 0.1% increase in propellant usage at most. In the trade studies presented in this paper, the basis of comparison is consistent and reasonable. Hence, incorporating high-fidelity trajectory models and modeling impulsive firings do not affect the arguments presented or conclusions drawn. For the sake of a direct comparison, all thrusters are used the same fashion in each mission scenario.

Thruster performance specifications were gleaned from product datasheets, published mission or experimental results, and personal communication with vendors. In some cases, however, a master equipment list (MEL) was not available. For these systems, the total system dry-mass information was estimated using legacy data. To build a MEL for these estimates, notional propulsion-system schematics were developed that included (as applicable for each system) valves, power conditioning electronics, transducers, and cathodes, among other components. A mass estimate was assigned to each component based on current technology. As a simple example, a schematic used for a monopropellant chemical propulsion system is provided in Fig. 1.

A more complex example of estimating the dry mass of a thruster system is provided in Fig. 2, the schematic used for Busek's BIT-3 gridded ion engine. The corresponding MEL for this estimate is provided in Table 1. Master equipment lists constructed for the current analyses are conservative estimates, including only components deemed necessary for a functional system when additional product information was not available.

Accuracy of the trade study results is affected by the numerical accuracy of the analyst settings and other calculation options available in GMAT as well as the precision of the propulsion-system performance data inputs. Integrator propagation accuracy on the millimeter scale and VNB frame angular position errors on the order of 5×10^{-8} deg published in GMAT verification and validation efforts were deemed acceptable for the trade study applications discussed here [26]. Variations exist across the testing regimes, settings, and conditions used by researchers and manufacturers to achieve each propulsion system's published performance data. These variations, which result in random and systematic errors unique to each propulsion-system performance data set, are considered negligible for the purposes of the current analyses.

Two baseline missions will be defined, representing different use cases for smallsats. Next, three categories of propulsion technologies will be introduced: cold gas, chemical, and electric propulsion

Table 1 Orbital elements for mission A: station keeping in a 10 year orbit

Component	Mass, g
Valves (×2)	132
Pressure transducer	74
Cathode (×2)	40
Power processing unit	405
Feed system support	50
Chassis	263
Fasteners	23
Gimbal	55
Thruster	157
Total estimated system dry mass	1199

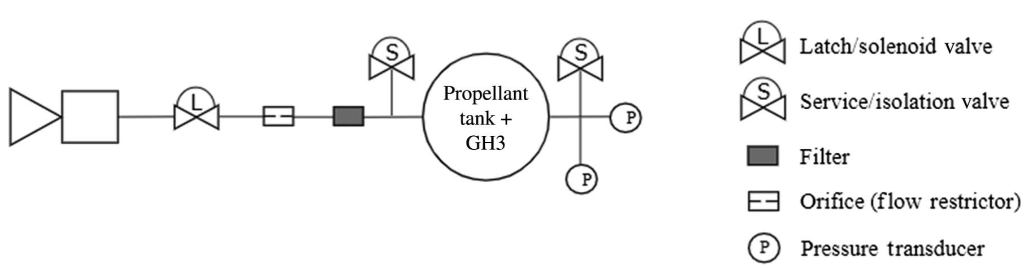

Fig. 1 Monopropellant chemical propulsion-system schematic.

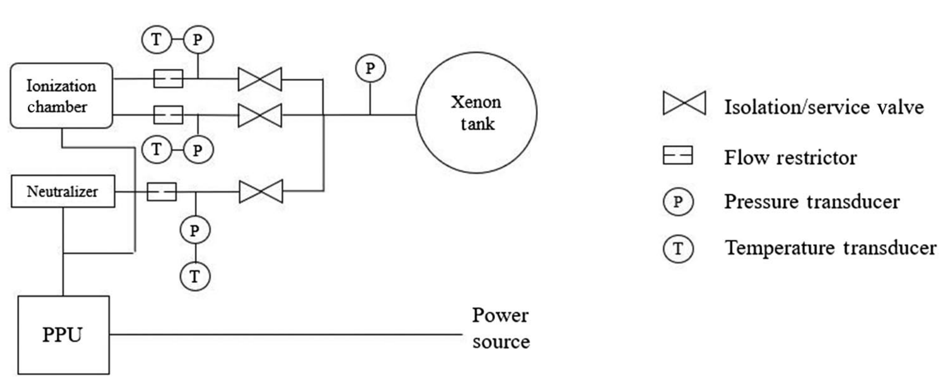

Fig. 2 Gridded ion electric propulsion-system schematic; PPU = power processing unit.

systems. Within each of these categories, performance data are provided for a selection of the discrete propulsion systems. For each baseline mission, performance of the selected propulsion technologies will be compared and analyzed. The top-performing systems are identified for both baseline missions. Finally, conclusions are drawn about which propulsion-system characteristics are best suited for the requirements prescribed in the baseline missions.

A. Baseline Missions

Given the wide range of applications for smallsats, the optimal propulsion system for a given space mission varies based on mission duration, operating environment, delta-V requirements, and orbit maneuvers, among other factors. To account for the use-case variability in comparing the performance of propulsion systems, two baseline missions were selected that represent different ends of the spectrum for smallsat applications: station keeping in a near-Earth orbit (mission A) and a high-impulse interplanetary trajectory (mission B). Station keeping, the maintenance of a spacecraft's proper position and orientation in a given orbit, is a well-established use for small propulsion systems. For the satellites in LEO, station keeping used to offset the effects of orbital perturbations are typically low-impulse thruster firings that occur periodically over a long orbit lifetime. Interplanetary missions, on the other hand, are an emerging use case for smallsats and have been gaining popularity in recent years. Unlike the station-keeping scenario, an interplanetary smallsat mission would typically require a high-impulse thruster firing over a shorter mission lifetime. Detailed descriptions of missions A and B are provided as follows.

1. *Mission A: Station Keeping in a 10 Year Orbit*

Mission A assumed a 400 km circular orbit in LEO, like that of the International Space Station. The orbital elements are listed in Table 2. A wet mass of 10 kg was allocated for a 6U CubeSat in the vertical configuration, where the 2U side was sun facing and the 3U side was the primary drag surface. The 6U CubeSat has the following overall dimensions: $12 \times 24 \times 36$ cm. The drag coefficient and coefficient of reflectivity were taken to be 2.2 and 1.8, respectively. The solar radiation pressure was assumed negligible compared to the drag force for a CubeSat operating in LEO.

In the mission A scenario, the orbit was propagated to an altitude of 100 km, which was considered the "decay point." For each propulsion system, a range of thrust levels was tested to determine the length of time required for the orbit to decay to 100 km. Drag and solar radiation pressure depend on the spacecraft's surface area, which was held constant in GMAT. Hence, mission lifetime was solely a function of the total impulse provided by the propulsion system. Figure 3 shows the orbit lifetime achieved across a range of total impulse for the 10 kg satellite in LEO.

General Mission Analysis Tool was used to calculate the maximum drag that occurred during the propagated orbit until decay. For each thrust level, a total impulse was calculated based on the time it took to decay, given that the thruster is assumed to be firing continuously. Next, the required delta-V was calculated for each total impulse. The ideal rocket equation, given in Eq. (1), was used to determine the wet mass (m_f) needed for each propulsion system's given dry mass (m_e), exhaust velocity, and required delta-V for each orbit lifetime:

Table 2 Orbital elements for mission A: station keeping in a 10 year orbit

Orbital element	Value
Semimajor axis	6782.64 km
Eccentricity	3.041×10^{-4}
Inclination	51.6 deg
Right ascension of the ascending node	36.923 deg
Argument of periapsis	185.1 deg
True anomaly	360 deg

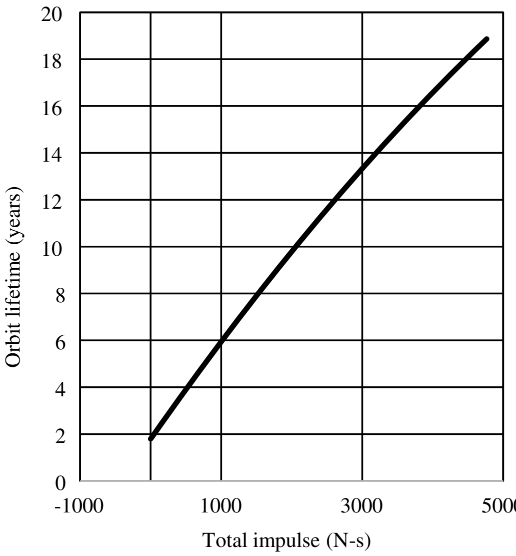

Fig. 3 Mission A: orbit lifetime as a function of total impulse.

$$\Delta v = v_e \, \ell n \left(\frac{m_f}{m_e} \right) \tag{1}$$

2. *Mission B: High Delta-V Interplanetary*

Mission B consists of a 2000 m/s delta-V with a burn time of less than 3 years. This scenario prescribed a total wet mass of 180 kg for the satellite, regardless of propulsion option. For each propulsion system, the dry mass was calculated using the ideal rocket equation across a range of values for delta-V. The number of thrusters was determined from the necessary mass flow rate. The total mass flow rate was then used to calculate the burn time. Hence, each time a thruster was added to the system, the dry mass was increased accordingly, and the delivered mass for each delta-V proportionally decreased. This process of adding thrusters to the total propulsion capability was iterated until a burn time of less than 3 years was achieved. Barring thruster start-up and shutdown transient effects, propellant use will be a function of the high delta-V impulse prescribed in this scenario. Differences in acceleration across propulsion systems are considered beyond the scope of the current trade studies, and their effect on orbit achieved is left for future work.

B. Small Propulsion Systems

Cold gas, chemical, and electric propulsion are three of the most popular propulsion-system types that mission designers must choose from in the smallsat propulsion market. This section provides a brief overview of each technology, as well as a general assessment of their primary advantages and disadvantages. The specific propulsion systems included in the trade studies are provided, along with a summary of their advertised performance and technological maturity, if available, in the form of a technology readiness level (TRL). For each propulsion-system model, performance data originating from laboratory or flight experiments are indicated with "Lab" and "Flight," respectively.

1. *Cold Gas Propulsion*

Cold gas propulsion systems are relatively simple technologies that operate by expanding an inert, nontoxic gaseous or liquid propellant. Cold gas systems are inexpensive, robust, and one of the most mature technologies for small spacecraft. Primary advantages include low weight and volume in addition to small impulse bit for attitude control. The primary disadvantage is their limited total impulse capability. Table 3 contains performance data for the cold gas propulsion systems analyzed in the trade studies.

2. *Chemical Propulsion*

Chemical propulsion systems generate thrust by ejecting gases formed during the combustion of liquid propellants. There is a rising popularity in alternative or "green" propellants that offer advantages in safety and handling compared to traditional chemical propellants, such as hydrazine. The primary advantage of chemical propulsion systems lies in their ability to perform high-thrust impulsive maneuvers or high-thrust-to-power ratios. The primary disadvantage of these systems is their relatively low specific impulse. Table 4 contains performance data for the chemical propulsion systems analyzed in the trade studies.

3. Electric Propulsion

Electric propulsion systems use electrical power to accelerate a propellant by electrical and/or magnetic means. The primary advantages of electric propulsion are high specific impulses, whereas the primary disadvantages of this technology are long maneuver times. The electrical power requirements of electric propulsion systems are particularly difficult to manage on small spacecraft buses, which are inherently more parsimonious with their power budgets than larger satellites. Moreover, the efficiency of electric propulsion devices typically decreases at power levels below 100 W [27]. The electric propulsion systems considered in this work represent a sampling of the wide variety of electric propulsion technologies developed to operate at nominal power levels less than 200 W. These technologies include gridded ion thrusters, pulsed plasma thrusters (PPTs), electrospray devices, and resistojets. Table 5 contains performance data for the electric propulsion systems analyzed in the trade studies.

III. Results

Results of the trade studies performed for both station-keeping and interplanetary baseline missions are presented in this section. For each propulsion system considered, the wet mass required as a function of increasing orbit lifetime is presented for the 10 kg spacecraft with a single thruster baselined in mission A, the 10 year station-keeping mission in LEO. Likewise, the delivered mass capability as a function of increasing delta-V is provided for the 180 kg spacecraft baselined in mission B, the high-impulse interplanetary trajectory. To quantify the performance of the propulsion systems, the delivered mass to orbit is assessed parametrically for each mission scenario. The 10 top-performing systems are identified for mission A and mission B in terms of their delivered mass to orbit.

Figures 4–7 show the required propulsion-system wet mass as a function of the mission's orbit lifetime. As expected, the wet mass required increases with increasing orbit lifetime for all propulsion systems. The rate of increase in wet mass required, indicated by the

Table 3 Cold gas propulsion technology

Developer	Model	Propellant	I_{sp}, s	Nominal thrust, mN	Nominal power, W	Predicted life, h	TRL
GOMspace [4–7]	MEMS cold gas (flight)	Methane	50–75	1.0	2	43,800	9
VACCO [8–10]	CPOD (laboratory)	R134a	40	25.0	5	——	6

Table 4 Chemical propulsion technology

Developer	Model	Propellant	Nominal propellant tank operating pressure, bar	Non-tank dry mass for first unit, kg	Non-tank dry mass for *n* th unit, kg	I_{sp}, s	Minimum impulse bit, mN · s	Nominal thrust, mN	Valve power, W	Predicted life, s	TRL
ECAPS [4]	1 N HPGP (flight)	LMP-103S	——	——	——	204–235	——	250–1000	——	——	8
Busek [4]	BGT-X5 (laboratory)	AF-M315E	27.58	0.12	0.12	220	50	500	20	——	5
Aerojet Rocketdyne [11,12]	MR-103D (flight)	Hydrazine	5.9–23.4	——	——	209–224	27	220–1020	8.25	——	9
Aerojet Rocketdyne [11,12]	MR-106E (flight)	Hydrazine	4.5–12.4	——	——	229–235	460	11,600–30,700	25.3	——	9
Moog[a]	MONARC-1 (flight)	Hydrazine	18.96	0.376	0.376	227.5	2.6	1000	18	200,000 (115 lbm)	9

[a]Personal communication with Shae Williams, 27 August 2018.

Table 5 Electric propulsion technology

Developer	Model	Type	Propellant	Advertised efficiency, %	I_{sp}, s	Minimum impulse bit, mN · s	Nominal thrust, mN	Nominal power, W	Predicted life, s	TRL
Accion Systems [13]	TILE-V1 (flight)	Electrospray	Ionic liquid	——	1500	<0.015	1.8	25	——	5
Accion Systems [4,14]	MAX-1 (laboratory)	Electrospray	Ionic liquid	60	2000	0.01	0.12	1.6	——	5
Aerojet Rocketdyne [15]	PRS-101 (flight)	PPT	Solid Teflon	>80	1350	——	1.2	100	——	9
ArianeGroup [16]	RIT-μX (laboratory)	Gridded ion	Xe	——	300–3000	——	0.05–0.5	<50	>20,000	5
ArianeGroup [16]	RIT 10 EVO (laboratory)	Gridded ion	Xe	——	>1900	——	5.0	145	>20,000	——
EADS Astrium[17]	μNRIT-2.5 (laboratory)	Gridded ion	Xe	15–50	363–2861	——	0.5	13–34	——	——
Busek [18]	BIT-3 (laboratory)	Gridded ion	Xe	25	2000	——	1.1	75	20,000	65
Busek [2,20]	BmP-220 (flight)	PPT	Solid Teflon	——	536	0.02		1.5–7.5	——	58
Busek [19,21]	BET-1mN (laboratory)	Electrospray	Ionic liquid	31	800	——	0.7	15	——	5
Busek [20]	BET-3100-P (laboratory)	Electrospray	Ionic liquid	——	1000–1800	——	0.005–0.01	5.5	——	6
Busek [22]	Micro-Resistojet (laboratory)	Resistojet	Ammonia	——	150	——	2–10	3–15	——	5
VACCO[23]	PUC (laboratory)	Resistojet	SO_2	50	47–70	1.0	4.5–5.5	15	——	6
Mars Space [24]	PPTCUP (flight)	PPT	Solid Teflon	4.8–5.7	600	0.04	0.04	2	——	8
MIT [4,21,25]	S-iEPS (laboratory)	Electrospray	Ionic liquid	71	1160	——	0.074	1.5	——	6

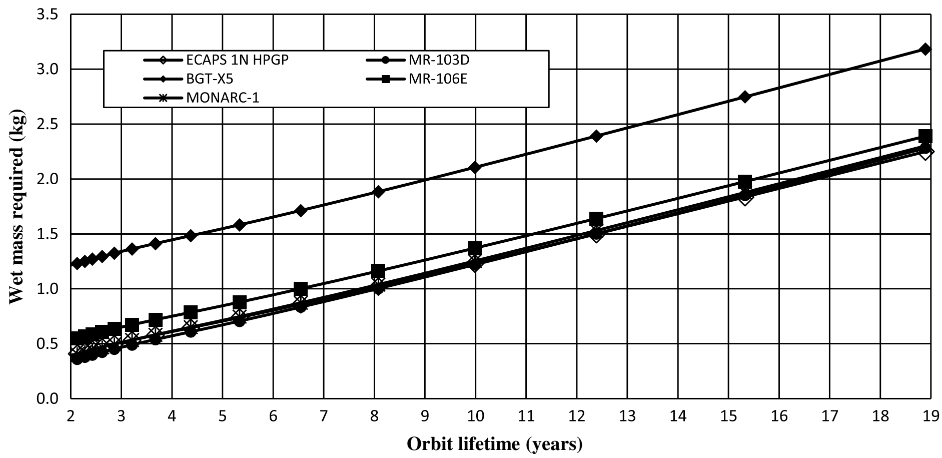

Fig. 4 Mission A: wet-mass requirements for chemical propulsion systems.

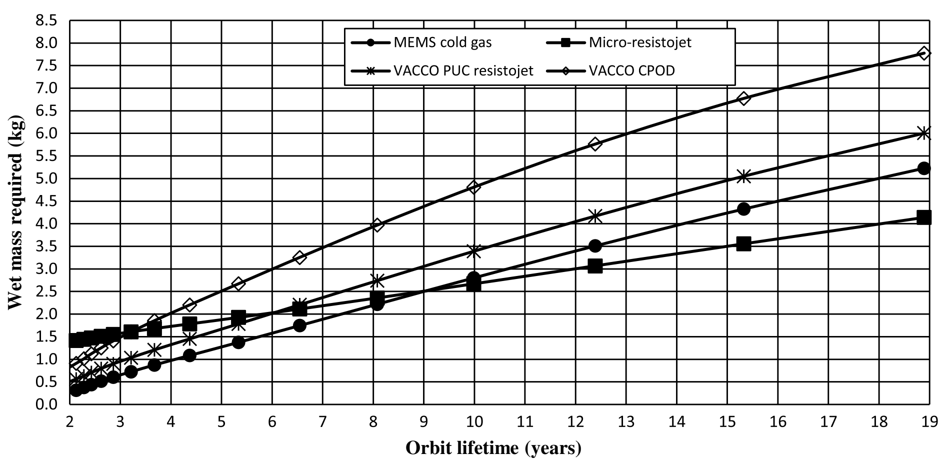

Fig. 5 Mission A: wet-mass requirements for cold gas and resistojet devices.

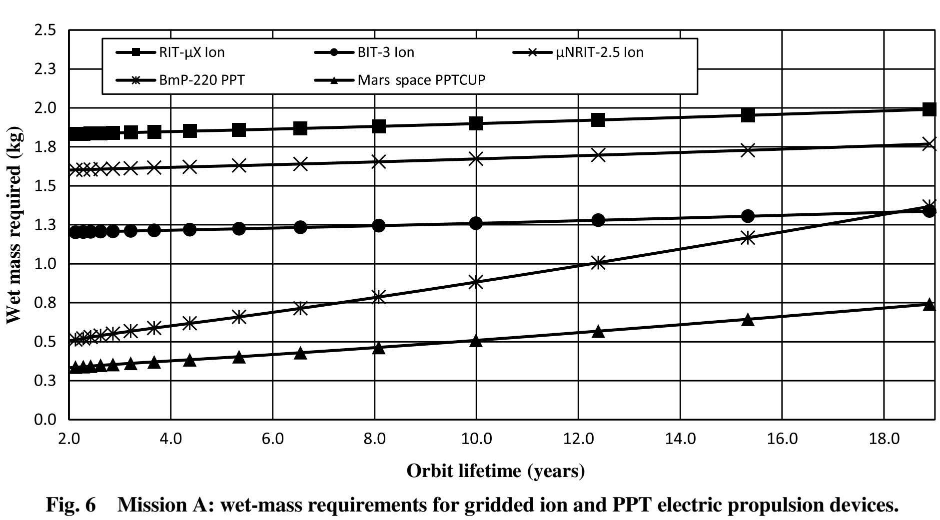

Fig. 6 Mission A: wet-mass requirements for gridded ion and PPT electric propulsion devices.

slopes of the curves, is notably higher for the chemical propulsion systems [Busek's BGT-X5, Aerojet Rocketdyne's MR-106E and MR-103D, Moog's MONARC-1, and ECAPS's 1 N High Performance Green Propulsion (HPGP) systems], shown in Fig. 4, and the cold gas systems [VACCO's CubeSat Proximity Operations Demonstration (CPOD) and GOMspace's microelectromechanical system (MEMS) cold gas], shown in Fig. 5. This indicates that cold gas and chemical propulsion systems are more sensitive to increases in orbit lifetime than electric propulsion systems. The exceptions are the two resistojet technologies included among the electric propulsion systems analyzed [VACCO's Propulsion Unit for CubeSats (PUC) and Busek's Micro-Resistojet], also shown in Fig. 5, which both exhibit significantly larger changes in wet mass required for increased orbit lifetime than the other electric propulsion technologies included in the analyses. The bulk of the electric propulsion technologies considered in the trade studies demonstrates low sensitivity to increases in orbit lifetime, as indicated by the relatively small slopes of the curves in Figs. 6–8. The electrospray devices shown in Fig. 7 perform

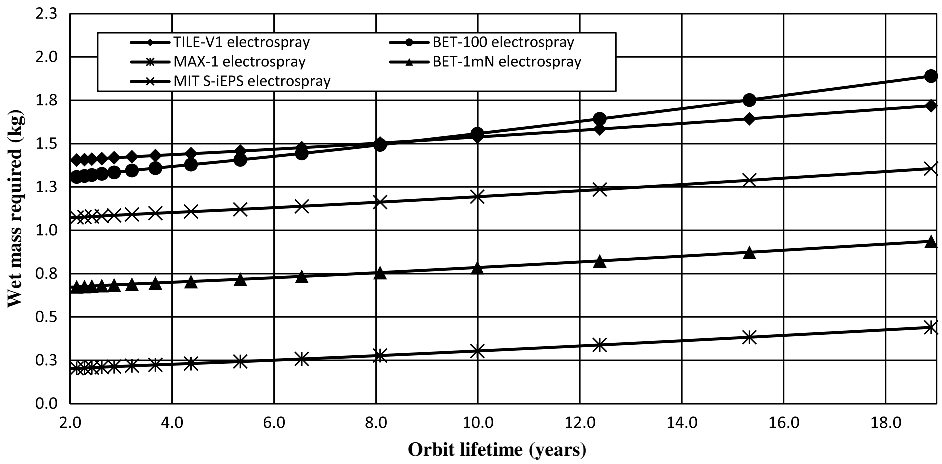

Fig. 7 Mission A: wet-mass requirements for electrospray electric propulsion devices.

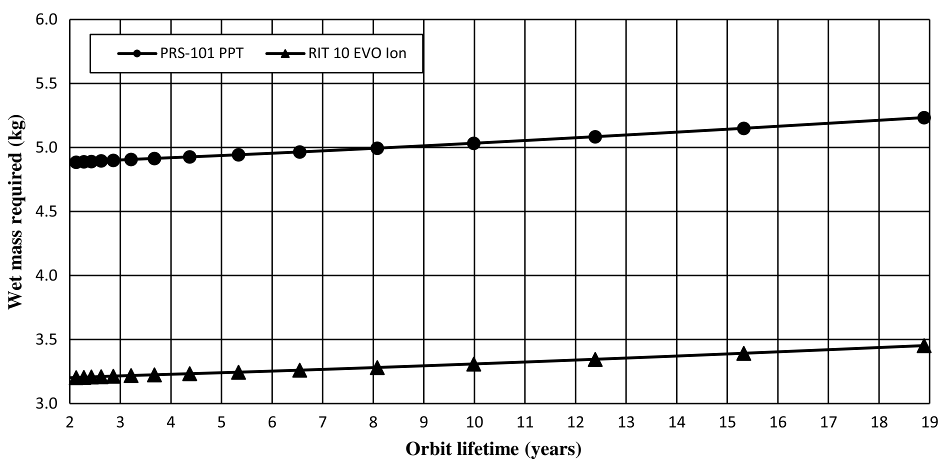

Fig. 8 Mission A: highest initial wet-mass requirements for propulsion systems included in trade studies.

well in this scenario, requiring relatively little additional wet mass with increasing orbit lifetime. Aerojet Rocketdyne's PRS-101 PPT and ArianeGroup's RIT 10 EVO gridded ion thruster, shown in Fig. 8, require a higher wet mass for short mission durations, approximately 2–3 more kilograms of propellant than the average-performing system in this grouping of electric propulsion technologies. However, consistent with the trends observed for other electric propulsion technologies, the effect of increasing orbital lifetime on the additional wet mass required is small compared to cold gas and chemical propulsion systems.

Figure 9 ranks the 10 top-performing propulsion systems in terms of their delivered mass capability for a 10 kg spacecraft continuously firing a single thruster over a 10 year orbit lifetime. All the highest-performing systems in this scenario are electric propulsion systems, with Accion System's MAX-1 electrospray propulsion system as the top performer. The MAX-1 electrospray system exhibits both a high-thrust-to-power ratio (nominally 0.075 mN/W) and a high I_{sp} (2000 s). For comparison, the next highest-performing system in this category is Mars Space's PPT for CubeSat Propulsion (PPTCUP) pulsed plasma device with a thrust-to-power ratio of 0.02 mN/W and I_{sp} of 600 s.

The next set of results pertain to mission B, the interplanetary scenario with an orbit lifetime of 3 years and a prescribed wet mass of 180 kg for the satellite. Figures 10–14 show the delivered mass capability as a function of increasing delta-V. For all systems, the delivered mass decreases with increasing delta-V, which reflects the fact that more of a spacecraft's mass budget is needed for propellant with high-impulse maneuvers. For zero delta-V, some propulsion systems have a delivered mass capability close to 180 kg, a result of a

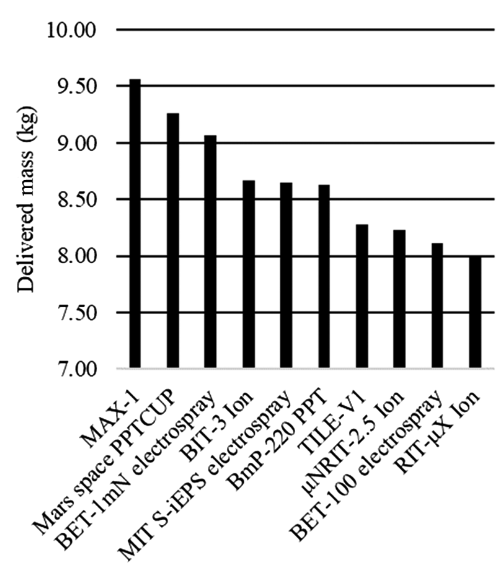

Fig. 9 Mission A: top 10 propulsion systems for a delivered mass capability.

low dry mass and low number of thrusters required, as is the case for the cold gas and chemical propulsion systems.

Figure 10 indicates that gridded ion thrusters can deliver the most mass to orbit with a 2000 m/s delta-V, as shown with Busek's BIT-3, ArianeGroup's RIT 10 EVO, and EADS Astrium's μNRIT-2.5

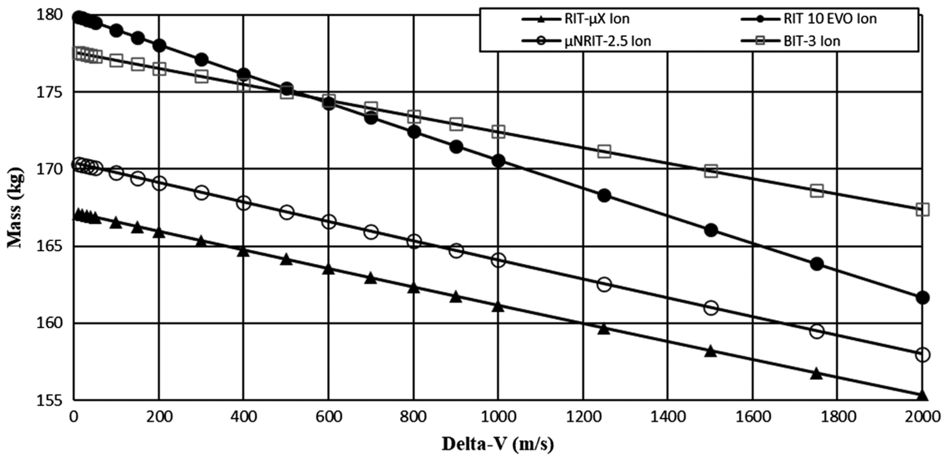

Fig. 10 Mission B: delivered mass to orbit for gridded ion electric propulsion devices.

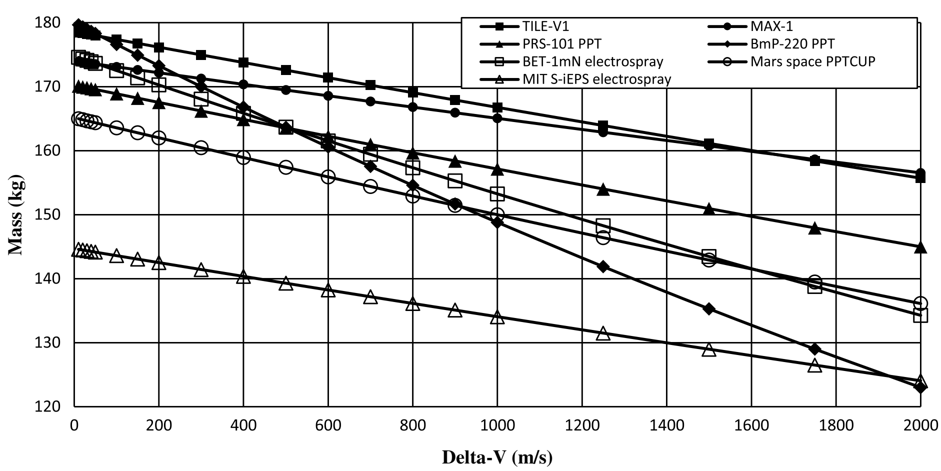

Fig. 11 Mission B: delivered mass to orbit for electrospray and PPTs.

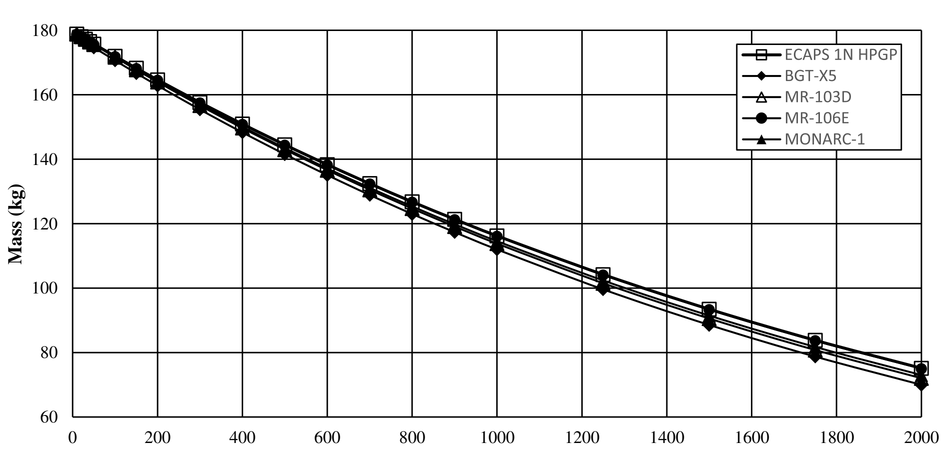

Fig. 12 Mission B: delivered mass to orbit for chemical propulsion systems.

gridded ion thruster systems. The propulsion systems analyzed have comparable delivered mass capabilities with no impulse burns (approximately 165–180 kg), with the exception of Massachusetts Institute of Technology's (MIT) S-iEPS electrospray thruster in Fig. 11, which delivers roughly 20–40 kg less before performing any delta-V burns. The results for the chemical propulsion technologies, shown in Fig. 12, demonstrate a nonlinear decrease in delivered mass capability. Results for the chemical propulsion systems are grouped tightly together for the first 1000 m/s of delta-V. For ease of comparison, Fig. 13 provides the results over a limited range of delta-V from 1000 to 2000 m/s. Figure 14 shows that, as delta-V is increased from 0 to 1000 m/s, the cold gas propulsion systems and resistojet electric propulsion systems analyzed (VACCO's CPOD, GOMspace's MEMS, VACCO's PUC, and Busek's Micro-Resistojet) exhibit rapid decreases in delivered mass capability compared to the other propulsion systems considered.

The 10 top-performing systems for the scenario outlined in mission B, a 2000 m/s delta-V with a burn time of less than 3 years, are

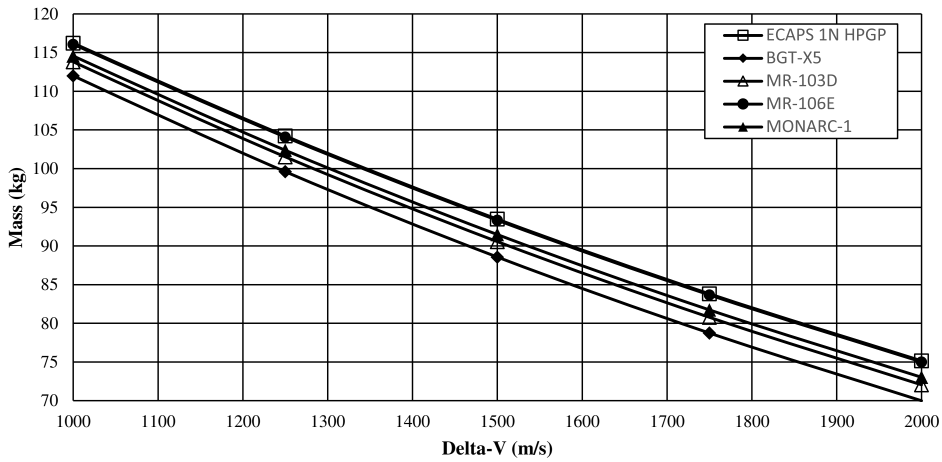

Fig. 13 Mission B: delivered mass to orbit for chemical propulsion systems over a limited delta-V range.

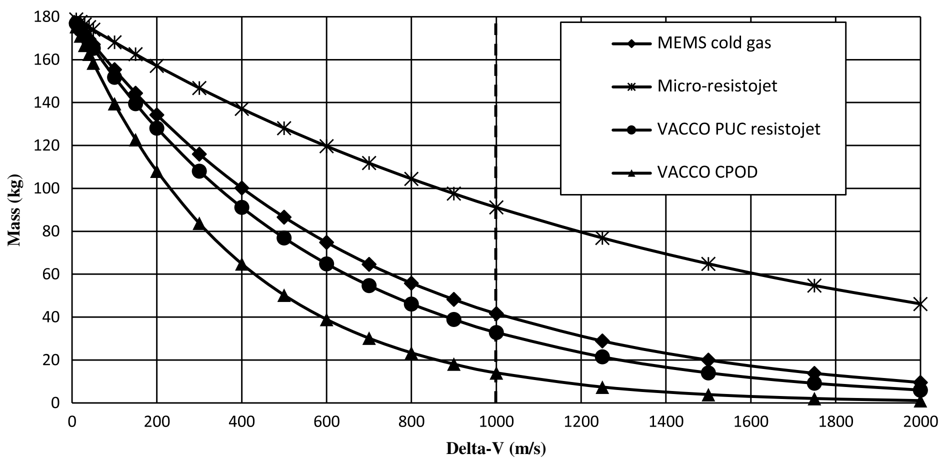

Fig. 14 Mission B: delivered mass to orbit for cold gas and resistojet devices.

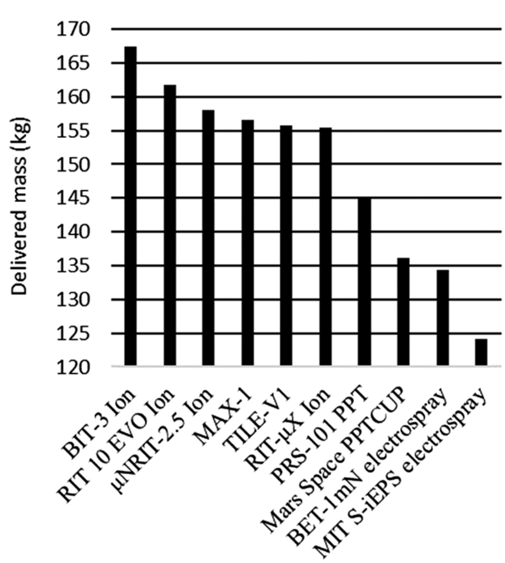

Fig. 15 Mission B: top 10 propulsion systems for delivered mass capability.

given in Fig. 15. Once again, electric propulsion devices make up all the top-performing systems. In this scenario, gridded ion thrusters perform best. This result is congruous with the results shown in Fig. 10, which showed that gridded ion thrusters perform well with high delta-V impulses.

IV. Discussion

For both mission scenarios considered in the current study, electric propulsion systems typically outperformed chemical and cold gas propulsion systems. Resistojet devices were the exception, as they were not favorable options in either mission scenario. Resistojets have a robust history of spaceflights, but are fundamentally limited by the maximum temperatures their heating elements can withstand during operation, which puts them at the lower end of the I_{sp} range for electric propulsion technologies. Furthermore, between the station-keeping and interplanetary missions, variations were observed in which type of electric propulsion technology performed best. For the 10 year station-keeping orbit, electrosprays tended to outperform gridded ion engines and PPTs. The relatively small size and number of components of electrospray propulsion systems result in a low dry mass compared to other propulsion-system types. A different trend was observed for the high delta-V interplanetary case, where gridded ion engines generally outperformed the other types of electric propulsion systems. For a given total dry mass among the systems considered in the current analyses, the I_{sp} is often significantly higher for gridded ion thrusters. As described in the methodology section, additional thrusters were added to increase acceleration on low-thrust systems to achieve the prescribed mission requirements. Thus, the performance of gridded ion propulsion systems demonstrates the significance of I_{sp} with respect to acceleration, given that gridded ion systems outperformed the competition even when compensating for thrust levels.

The effect of increasing orbit lifetime varied significantly with propulsion-system type. Cold gas, chemical, and resistojets required less wet mass early in the mission than most electric propulsion systems, but demonstrated higher sensitivity to increases in orbital lifetime, quickly surpassing the wet-mass requirements of the other technologies as years were added to the mission simulation. After the first year of the mission, cold gas systems required five to seven times more wet mass with the addition of 15 years to the orbit lifetime. Chemical systems required approximately twice as much wet mass, and resistojet technologies required approximately four to six times as much wet mass across the same orbit lifetime interval.

Neglecting resistojets, wet-mass requirements for electric propulsion systems did not change as drastically with increases in orbit lifetime. Busek's BmP-220 PPT, which uses solid Teflon as a propellant and has one of the lowest nominal power requirements of the electric propulsion technologies considered, required approximately twice as much additional wet mass with 15 years added to its orbit lifetime. All other gridded ion engines, electrospray, and pulsed plasma devices required less than half as much additional wet mass with the same addition of 15 years to orbit lifetime after the first year of the mission. The impervious nature of electric propulsion-system wet-mass requirements to increases in mission timelines is particularly valuable for smallsat applications with inherently tight mass budgets.

The degree to which there is a tradeoff between a satellite's delivered mass to orbit capability and the mission's delta-V requirement is also influenced by propulsion-system type. In what is often referred to as "the tyranny of the rocket equation," higher delta-V requirements translate to more mass required for propellant, which leaves less mass available for payload. Cold gas and resistojet technologies were most sensitive to this tradeoff. VACCO's CPOD system was unable to deliver any payload mass to orbit with a 2000 m/s delta-V. The best performer among the cold gas and resistojet systems considered was Busek's Micro-Resistojet. Even so, Busek's Micro-Resistojet delivered approximately 30% less mass to orbit at 1000 m/s delta-V and over 50% less mass to orbit at 2000 m/s delta-V than all other electric propulsion and chemical propulsion systems considered.

Across the same delta-V range of 0–2000 m/s, the variability of all other electric propulsion technologies in delivered mass capability ranged from an overall decrease of approximately 10 kg in the case of ArianeGroup's RIT-μX gridded ion engine to more than 50 kg in the case of Busek's BmP-220 PPT. These examples are reflective of the technology groupings as a whole: gridded ion engines delivered more mass to orbit at the upper end of the delta-V range than other technologies in this category, whereas PPTs had sharper declines in capability with increasing delta-V. Results in delivered mass to orbit across the 0–2000 m/s delta-V interval were more tightly clustered for chemical propulsion technologies, where all five systems considered demonstrated overall decreases between 100 and 110 kg. For a delta-V of 1000 m/s, chemical propulsion systems delivered anywhere from 15 to 50% less mass to orbit than the electric propulsion technologies.

The best propulsion options for the LEO station-keeping case were the systems where increasing the orbit lifetime had little effect on the wet mass required. This trend was observed in electrospray and some PPT systems. Conversely, cold gas propulsion systems and resistojet electric propulsion systems exhibited the most sensitivity to increasing orbit lifetime in terms of their delivered mass capability and, as a result, are the least favorable options for the station-keeping scenario. Electric propulsion is a prime candidate for station keeping because the long time frames associated with maintaining a stationary orbit take advantage of the high efficiencies found in most electric propulsion devices. In addition, the low-thrust requirements needed for most station-keeping missions avoid electric propulsion's primary drawback of small impulse capability.

For the high impulse requirement and larger smallsat wet-mass allowance prescribed in the interplanetary mission scenario, gridded ion thrusters were the best options. The I_{sp} values associated with gridded ion thrusters were the highest of any category of propulsion system considered in the current analyses, which allow them to reach high velocities while consuming less fuel. In fact, gridded ion thrusters have a history of deep space applications, such as the NASA Solar Technology Application Readiness (NSTAR) engine used on the Deep Space 1 probe and variations of NSTAR that were used on the Dawn spacecraft [28].

Further analysis is required across more diverse baseline missions to fully understand the extent of the performance trends observed in the current analyses. Using the current smallsat market forecast, additional baseline missions can be crafted to reflect the intended uses for this class of spacecraft in the coming years. Future studies will also need to account for any updated performance numbers, which are likely to be significant in some instances given the advanced pace with which smallsat propulsion systems are evolving. Similarly, as more COTS smallsat propulsion systems enter the market, they should be added as future trade study inputs. Future work could also include high-fidelity modeling that optimizes thruster firing patterns for maximum lifetime.

V. Conclusions

Ultimately, the best smallsat propulsion system is determined by the mission application. Historically, cold gas and PPTs have been favorable options for attitude control, but they generally do not perform well for more ambitious maneuvers, such as high delta-V maneuvers and large orbital transfers. Small chemical thrusters, both hydrazine and green propellant varieties, are frequently selected for missions that require high delta-V budgets. Electric propulsion systems, gridded ion engines in particular, are able to achieve a remarkably high delta-V over a long period of time. The results of this study indicate that electric propulsion is a promising candidate for both long-duration and high delta-V smallsat missions.

References

[1] *SpaceWorks 2018 Nano/Microsatellite Market Forecast*, 8th ed., SpaceWorks Enterprises, Inc., 2018, https://www.spaceworks.aero/nano-microsatellite-forecast-8th-edition-2018/ [retrieved 12 Sept. 2020]

[2] Parker, K. I., "State-of-the-Art for Small Satellite Propulsion Systems," *2nd Planetary CubeSat Science Symposium*, NASA Goddard Space Flight Center, GSFC-E-DAA-TN33641, Greenbelt, MD, Sept. 2017, https://ntrs.nasa.gov/citations/20160010571.

[3] "General Mission Analysis Tool (GMAT)," Ver. R2016a, NASA Goddard Space Flight Center, GSC-17177-1, Greenbelt, Maryland, 2016, https://software.nasa.gov/software/GSC-17177-1 [retrieved 12 Sept. 2020].

[4] Agasid, E., Burton, R., Carlino, R., Defouw, G., Dono Perez, A., Göktuğ Karacalıoğlu, A., Klamm, B., Rademacher, A., Schalkwyck, R., Tilles, J., and Weston, S., "State of the Art of Small Spacecraft Technology," NASA TP 2018-220027, 2018.

[5] Lemmer, K., "Propulsion for CubeSats," *Acta Astronautica*, Vol. 134, May 2017, pp. 231–243. https://doi.org/10.1016/j.actaastro.2017.01.048

[6] Persson, S., Jacobsson, B., and Gill, E., "PRISMA—Demonstration Mission for Advanced Rendezvous and Formation Flying Technologies and Sensors," *Proceedings of the 56th International Astronautical Congress*, International Astronautical Congress Paper IAC-05-B5.6.B.07, Fukuoka, Japan, Oct. 2005.

[7] Wu, S., Mu, Z., Chen, W., Rodrigues, P., Mendes, R., and Alminde, L., "TW-1: A CubeSat Constellation for Space Networking Experiments," *Proceedings of the 6th European CubeSat Symposium*, European CubeSat Symposium, Estavayer-le-Lac, Switzerland, Oct. 2014, http://www.issibj.ac.cn/Program/Space_Science_School/1st_SSS_Pictures/201810/W020181025592116654480.pdf.

[8] Roscoe, C. W., Westphal, J. J., Griesbach, J. D., and Schaub, H., "Formation Establishment and Reconfiguration Using Differential Elements in J_2-Perturbed Orbits," *Journal of Guidance, Control, and Dynamics*, Vol. 38, No. 9, 2015, pp. 1725–1740. https://doi.org/10.2514/1.G000999

[9] Bowen, J., Villa, M., and Williams, A., "CubeSat Based Rendezvous, Proximity Operations, and Docking in the CPOD Mission," *Proceedings of the 29th Annual AIAA/USA Conference on Small Satellites*, Paper SSC15-III-5, 2015, p. 9.

[10] Kolmas, J., Banazadeh, P., Koenig, A. W., Macintosh, B., and D'Amico, S., "System Design of a Miniaturized Distributed Occulter/Telescope for Direct Imaging of Star Vicinity," *Proceedings of the 2016 IEEE Aerospace Conference*, Paper 8725, 2016, pp. 1–11.

[11] "Monopropellant Rocket Engines," Datasheet, Aerojet Rocketdyne, April 2006.

[12] "MR-103D 1N (0.2-lbf) Rocket Engine Assembly," Datasheet, Aerojet Rocketdyne, April 2006.

[13] "TILE-V1 Modular Small Satellite Propulsion," Datasheet, Accion Systems, Inc., 2016.

[14] "MAX-1 Scalable Electric Propulsion System for Small Satellites," Datasheet, Accion Systems, Inc., 2015.

[15] "PRS-101 Pulsed Plasma Thruster System," Datasheet, Aerojet Rocketdyne, 2006.

[16] Cortes Borgmeyer, S., "Electric Propulsion Systems and Components," Datasheet, ArianeGroup, https://www.space-propulsion.com/spacecraft-propulsion/propulsion-systems/electric-propulsion/index.html [accessed 19 Sept. 2020].

[17] Feili, D., Lotz, B., Bonnet, S., Meyer, B. K., and Loeb, W., "μNRIT-2.5—A New Optimized Microthruster of Giessen University," *Proceedings of the 31st International Electric Propulsion Conference*, Paper IEPC-2009-174, Ann Arbor, Michigan, 2009.

[18] "3 cm RF Ion Thruster BIT-3," Datasheet, Busek, 2014.

[19] "BET-1mN Busek Electrospray Thruster," Datasheet, Busek, 2016.

[20] "BET-100 Busek Electrospray Thruster," Datasheet, Busek, 2016.

[21] Keidar, M., Zhuang, T., Shashurin, A., Teel, G., Chiu, D., Lukas, J., Haque, S., and Brieda, L., "Electric Propulsion for Small Satellites," *Plasma Physics and Controlled Fusion*, Vol. 57, No. 1, 2015, Paper 014005. https://doi.org/10.1088/0741-3335/57/1/014005

[22] "Busek Micro-Resistojet," Datasheet, Busek, 2013.

[23] Carroll, D. L., Cardin, J. M., Burton, R. L., Benavides, G. F., Hejmanowski, N., Woodruff, C. A., Bassett, K., King, D. M., Laystrom-Woodard, J. K., Richardson, L., Day, C., Hageman, K., and Bhandari, R., "Propulsion Unit for CubeSats (PUC)," *Proceedings of the 62nd JANNAF Propulsion Meeting*, June 2015, Paper 4059.

[24] "Pulsed Plasma Thruster (PPT) Projects: PPT for Cubesat Propulsion (PPTCUP)," Mars Space Ltd., 2018, https://mars-space.co.uk/ppt [accessed 12 Sept. 2020].

[25] Krejci, D., Mier-Hicks, F., Fucetola, C., Lozano, P., Hsu Schouten, A., and Martel, F., "Design and Characterization of a Scalable ion Electrospray Propulsion System," *Proceedings of the 34th International Electric Propulsion Conference*, Paper IEPC-2015-0149, 2015.

[26] Hughes, S. P., Qureshi, R. H., Cooley, D. S., Parker, J. K., and Grubb, T. G., "Verification and Validation of the General Mission Analysis Tool (GMAT)," *Proceedings of AIAA/AAS Astrodynamics Specialist Conference*, AIAA Paper 2014-4151, Aug. 2014.

[27] Levchenko, I., Xu, S., Teel, G., Mariotti, D., Walker, M. L. R., and Keidar, M., "Recent Progress and Perspectives of Space Electric Propulsion Systems Based on Smart Nanomaterials," *Nature Communications*, Vol. 9, No. 1, 2018, pp. 1–19.

[28] Webb-Mack, Z., "A Brief History of Ion Propulsion," NASA Solar System Exploration, News Feature 723, Aug. 2018, https://solarsystem.nasa.gov/news/723/a-brief-history-of-ion-propulsion/ [retrieved 12 Sept. 2020].

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