Propulsion

Introduction

There is currently a wide range of technologies for propulsion systems, however the miniaturization of these systems for small spacecraft has been particularly challenging. The purpose of this chapter is to identify and analyze the current developmental status of propulsion technologies for small spacecraft and to present an overview of the available systems. Performance tests and technology demonstrations were considered in order to assess the maturity and robustness of each system. Some of the current systems are adaptable to a large variety of smaller buses. Since the last edition of this report in 2015, there have been several small satellite propulsion flight demonstrations. Due to the continuous redesign of smallsat propulsion systems post flight demonstration, their associated TRL will be reflected to match the NASA Standard guidelines (found on NASA Nodis website). A system is only TRL 9 when the actual system is flight proven through successful mission operations with documented mission operation results on a small spacecraft. A redesign or change in the component architecture or environment drops the TRL to 5 until a proven demonstration takes place in a high-fidelity environment (NASA NPR 7123.1B). Additionally, it should be noted that flight proven systems on a small spacecraft that is larger than a nanosatellite may still require testing for a smaller (nanosatellite) platform.

Cold gas or pulsed plasma systems for small delta-V maneuvers are fairly well established. However, higher delta-V applications require propulsion systems that are still in development. Small spacecraft buses other than CubeSats have more flexibility to accommodate systems with several thruster units to provide more attitude control and also large single axis maneuvers. Missions have demonstrated these technologies successfully, and the performance data gathered has paved the way for future modifications of the existing hardware in order to re-adapt the designs to satisfy demanding constraints.

Electric and chemical systems have experienced a significant maturation process with respect to the previous 2015 report. Thrust stand measurements in vacuum and lifetime tests have been performed for an extensive variety of devices and a serious effort has been made by several companies, agencies and institutions to satisfy small spacecraft requirements. Fundamental components, such as Power Processing Units (PPUs) and particular mass, power and volume constraints, have been adjusted to smaller buses. Electric propulsion devices that have been miniaturized to successfully adapt to small buses and low thrust options for CubeSats, such as electrosprays or Pulsed Plasma Thrusters (PPT), enable easy integration due to their low degree of complexity. For more ambitious mission concepts that require higher delta-V, technologies such as Hall Effect and ion systems, are still being developed.

New alternative (green) propellants offer advantages in safety and handling over traditional hazardous propellants, such as hydrazine. Finally, in regards to propellant-less systems, the launch of LightSail has advanced the state-of-the-art of solar sails for small spacecraft.

This section considers systems that have flown, or have been actively in development over the last few years, to account for the most recent technological advances. The chapter is divided in three main categories in the "State of the Art" and "On the Horizon" sections: chemical, electric and propellant-less systems, which are divided into smaller subsections depending on the type of thrust generation. The "State of the Art" section is defined as technology assessed at TRL 5 and higher, while the "On the Horizon section" describes technology assessed at TRL 4 and below.
Whenever pertinent, this report considers complete propulsion systems to be composed of thrusters, feed systems, propellant storage and power processing units, but not the electrical power supply. In addition, for some subsections, single thruster heads are also introduced. Development on propulsive modules used for deorbit maneuvers, like solar sails, will be addressed. Table 4-1 shows a summary of the current state-of-the-art for different propulsion methods.

The author would like to highlight that the presented tables are not intended to be exhaustive but to provide an overview of current state-of-the-art technologies and their development status for this small spacecraft subsystem. There was no intention of mentioning certain companies and omitting others based on their technologies.

<table>
<thead>
<tr>
<th>Product</th>
<th>Thrust</th>
<th>Specific Impulse (s)</th>
<th>TRL Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrazine</td>
<td>0.5 – 30.7 N</td>
<td>200-235</td>
<td>9</td>
</tr>
<tr>
<td>Cold Gas</td>
<td>10 mN – 10 N</td>
<td>40 – 70</td>
<td>GN2/Butane/R236fa 9</td>
</tr>
<tr>
<td>Alternative (Green) Propulsion</td>
<td>0.1 – 27 N</td>
<td>190 – 250</td>
<td>HAN 6, ADN 9</td>
</tr>
<tr>
<td>Pulsed Plasma and Vacuum Arc Thrusters</td>
<td>1 – 1300 μN</td>
<td>500 – 3000</td>
<td>Teflon 7, Titanium 7</td>
</tr>
<tr>
<td>Electrospray Propulsion</td>
<td>10 – 120 μN</td>
<td>500 – 5000</td>
<td>7</td>
</tr>
<tr>
<td>Hall Effect Thrusters</td>
<td>10 – 50 mN</td>
<td>1000 – 2000</td>
<td>Xenon 7, Iodine 3</td>
</tr>
<tr>
<td>Ion Engines</td>
<td>1 – 10 mN</td>
<td>1000 – 3500</td>
<td>Xenon7, Iodine 4</td>
</tr>
<tr>
<td>Solar Sails</td>
<td>0.25 – 0.6 mN</td>
<td>N/A</td>
<td>6 (85 m²), 7 (35 m²)</td>
</tr>
</tbody>
</table>

State of the Art

Chemical Propulsion Systems

Chemical propulsion systems are designed to satisfy high thrust impulsive maneuvers. They are associated with lower specific impulse compared to their electric counterparts, but have significantly higher thrust to power ratios.

Hydrazine Propellant

There are a significant number of mature hydrazine propulsion systems used in large spacecraft that present a generally reliable option as mass and volume of these compact systems allow them to be a suitable fit for some small spacecraft buses. Thrusters that perform small corrective maneuvers and attitude control in large spacecraft may be large enough to perform high thrust maneuvers for small spacecraft and can act as the main propulsion system. Hydrazine propulsion systems typically incorporate a double stage flow control valve that regulates the propellant supply and a catalyst bed heater with thermal insulation. Typically, they have the advantage of being
qualified for multiple cold starts which may be beneficial for power-limited buses if the lifespan of the mission is short. Hydrazine specific impulses are achievable in the 150-250 s range. Because hydrazine systems are so widely used for large satellites, a robust ecosystem of components exist, and hydrazine propulsion systems are custom-designed for specific applications using available components.

Airbus Defense and Space has developed a 1-N class hydrazine thruster that has extensive flight heritage, including use on the small spacecraft, ALSAT-2. Aerojet Rocketdyne has leveraged existing designs with flight heritage from large spacecraft that may be applicable to small buses, such as the MR-103 thruster used on New Horizons for attitude control application (Stratton 2004). Other Aerojet Rocketdyne thrusters potentially applicable to small spacecraft include the MR-111 and the MR-106 (Aerojet Rocketdyne 2015).

The CubeSat High-Impulse Adaptable Modular Propulsion System (CHAMPS) project leverages the miniaturization effort performed for previous small hydrazine thrusters to develop CubeSat monopropellant propulsion systems. These modules satisfy a wide range of maneuvers from station-keeping and orbit transfers to momentum management. There are various configurations, such as the MPS-120, that support up to four 1-N hydrazine thrusters configured to provide pitch, yaw, and roll control as well as single-axis thrusting vectors. The MPS-120 was selected and funded by NASA to go through extensive testing. The 3D printed titanium isolation and tank systems were demonstrated in mid-2014 and one engine performed a hot fire test in late 2014 (Carpenter, et al. 2014). Currently, this system has some final development tasks remaining and depending on the level of qualification required, a first system could be delivered in the next year. The TRL is assessed at 5.

Additional versions of the MPS series are under development that use various thruster technologies such as cold gas (MPS-110), non-toxic AF-M315E propellant (MPS-130) or electric propulsion devices (MPS-160) (Aerojet Rocketdyne 2015). Aerojet Rocketdyne is also developing integrated modular propulsion systems for larger small spacecraft. The MPS-220 consists of two 22-N primary engines and eight 1-N auxiliary hydrazine thrusters (Aerojet Rocketdyne 2015).

Moog ISP has extensive experience in the design and testing of propulsion systems and components for large spacecraft. These may also apply for smaller platforms as some of their flight-proven thrusters are light-weight and have moderate power requirements. The MONARC-5 thrusters flew on NASA JPL’s Soil Moisture Active Passive (SMAP) spacecraft in 2015 and provided 4.5 N of steady state thrust. Other thrusters potentially applicable to small spacecraft buses include the MONARC-1 and the MONARC-22 series (Moog ISP 2014). While all of these MONARC thrusters have extensive flight heritage on larger spacecraft, there is no evidence they have flown on a small spacecraft, making the TRL for small spacecraft application 5.

**Alternative (Green) Propellants**

Alternative, ‘green fuel’ propellants have a reduced toxicity due to the lower danger of component chemicals and significantly reduced vapor pressure as compared to hydrazine. The ‘green’ affiliation results in the propellant being less flammable which in turn requires fewer safety requirements for handling, and potentially removes Self-Contained Atmospheric Protective Ensemble (SCAPE) suit requirements. This reduces operational oversight by safety and emergency personnel.

Range Safety AFSPCMAN91-710 requirements state that if a propellant is less prone to external leakage, which is seen with the alternative “green” systems due to higher viscosity of the propellant, the hazardous classification is reduced. External hydrazine leakage is considered “catastrophic,” whereas using alternative “green” propellants reduces the hazard severity
classification to “critical” and possibly “marginal” per MIL-STD-882E (Standard Practice for System Safety) (R. M. Spores 2013). A classification of “critical” or less only requires two-seals to inhibit external leakage, meaning no additional latch valves other isolation devices are required in the feed system (R. M. Spores 2013). While these propellants are not safe for consumption, they have been shown to be less toxic compared to hydrazine. This is primarily due to alternative propellants being less flammable; nontoxic gasses (such as water vapor, hydrogen and carbon dioxide) are released when combusted.

Fueling spacecraft with green fuels, a parallel operation, may require a smaller exclusionary zone, allowing for accelerated launch readiness operations. These alternative propellants are generally less likely to exothermically decompose at room temperature due to higher ignition thresholds. Therefore they require fewer inhibit requirements, fewer valve seats for power, less stringent temperature requirements, and lower power requirements for system heaters.

Alternative propellants also provide higher performance than the current state-of-the-art fuel and have higher density-specific impulse achieving improved mass fractions. As a majority of these non-toxic propellants are in development, systems using these propellants present technical challenges including increased power consumption and a smaller selection of materials due to higher combustion temperatures. The primary ionic liquid propellants with flight heritage or upcoming spaceflight plans are Ammonium DiNitramide (ADN)-based LMP-103S and AF-M215E, and AF-M315E, a Hydroxyl Ammonium Nitrate (HAN)-based monopropellant. Table 4-2 lists the current state-of-the-art in green propellants. It should be noted that are two variations of the LMP-103S.
## Table 4-2: Green Propulsion Systems

<table>
<thead>
<tr>
<th>Product</th>
<th>AND or HAN based Propellant</th>
<th>Manufacturer</th>
<th>Thrust (N)</th>
<th>Specific Impulse (s)</th>
<th>TRL Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR-1</td>
<td>HAN</td>
<td>Aerojet Rocketdyne</td>
<td>0.26 – 1.42</td>
<td>231</td>
<td>6</td>
</tr>
<tr>
<td>GR-22</td>
<td>HAN</td>
<td>Aerojet Rocketdyne</td>
<td>5.7 – 26.9</td>
<td>248</td>
<td>5</td>
</tr>
<tr>
<td>1 N HPGP</td>
<td>ADN</td>
<td>Bradford Engineering</td>
<td>0.25 – 1.00</td>
<td>204 – 235</td>
<td>9</td>
</tr>
<tr>
<td>HYDROS-C</td>
<td>Other</td>
<td>Tethers Unlimited, Inc.</td>
<td>1.2</td>
<td>310</td>
<td>6</td>
</tr>
<tr>
<td>AMAC</td>
<td>Other</td>
<td>Busek</td>
<td>0.425</td>
<td>225</td>
<td>5</td>
</tr>
<tr>
<td>Lunar Flashlight MiPS</td>
<td>ADN</td>
<td>VACCO</td>
<td>0.4</td>
<td>190</td>
<td>6</td>
</tr>
<tr>
<td>Integrated Propulsion System</td>
<td>ADN</td>
<td>VACCO</td>
<td>4.0</td>
<td>220</td>
<td>6</td>
</tr>
<tr>
<td>ArgoMoon Hybrid MiPS</td>
<td>ADN</td>
<td>VACCO</td>
<td>0.1</td>
<td>190</td>
<td>6</td>
</tr>
<tr>
<td>BGT-X5</td>
<td>HAN</td>
<td>Busek</td>
<td>0.5</td>
<td>220</td>
<td>5</td>
</tr>
<tr>
<td>EPSS C1K</td>
<td>ADN</td>
<td>NanoAvionics</td>
<td>0.3</td>
<td>252</td>
<td>7</td>
</tr>
<tr>
<td>Green Hybrid</td>
<td>Other</td>
<td>Utah State</td>
<td>8</td>
<td>215</td>
<td>6</td>
</tr>
</tbody>
</table>

The Ecological Advanced Propulsion Systems, Inc. (ECAPS) High Performance Green Propulsion (HPGP) system (Figure 4.1), uses ammonium dinitramide-based LMP-103S as propellant. Its density is slightly higher than hydrazine (1.24 gcm\(^{-3}\) vs 1.02 gcm\(^{-3}\)). HPGP 1-N systems are being implemented in SkySat missions such as SkySat-3 (120 kg mass, launched June 2016), and SkySat block-I, and as of October, 2017, 13 SkySat small spacecraft were launched and are fully operational, making the system TRL 9. The HGPG systems are designed for three different thrust magnitudes: 5-N and 22-N, with higher thrust systems in development (Persson 2015).

VACCO partnered with Bradford Engineering (formerly ECAPS) to design a self-contained unit that can deliver up to 3320 N-s of total impulse and can be adapted for different sizes, from 0.5U to 1U. The Micro Propulsion System (MiPS) is designed to meet the specific CubeSat standards and has four 100-mN ADN-propellant thrusters. This unit also has an ArgoMoon Prolusion thruster that incorporates one 100-mN ADN thruster and four 10-mN cold gas thrusters for attitude control, providing up to 783 N-s of total impulse for main delta-V applications and 72 N-s for Reaction

![Figure 4.1: ECAPS HPGP thruster. Image courtesy of SSC ECAPS.](image-url)
Control Systems (RCS) (VACCO Industries 2015). There are several upcoming opportunities for this module to be flight-proven: a hybrid MiPS system is being developed for the ArgoMoon nanosatellite program that is planned to launch in 2020 with EM-1, as well as four MiPS thrusters that will be flown on Lunar Flashlight, a 6U spacecraft. The thrusters for this mission are undergoing qualification testing in May, 2019.

Another alternative propellant in development is the U.S. Air Force's AF-M315E (HAN-based). Aerojet Rocketdyne is currently developing propulsion systems using this propellant. The AF-M315E has a density of 1.47 g cm\(^{-3}\) (about 45% more than hydrazine) and a specific impulse of 230 – 250 s. While some components have heritage from previous hydrazine systems, others that are compatible with AF-M315E propellant, such as valves and filters, are at TRL 6 (Spores, et al. 2014). The propulsion system will be flown as a technology demonstration on the NASA Green Propellant Infusion Mission (GPIM), scheduled to launch 2018-2019. This small spacecraft is designed to test the performance of this propulsion technology in space by using five 1 N class thrusters (GR-1) for small attitude control maneuvers (McLean, et al. 2015). Aerojet completed a hot-fire test of the GR-1 version in 2014 and further tests in 2015. Initial plans to incorporate the GR-22 thruster (22-N class) on the GPIM mission were deferred in mid-2015 in order to allow for more development and testing of the GR-22. As a result, the GPIM mission will only carry 1 GR-1 unit when launched (Masse, et al. 2016). The TRL is currently 6 for the GR-1 (Figure 4.2), and 5 for the larger GR-22 (Figure 4.3).

The AF-M315E propellant is used by a 0.5 N thruster that is being developed by Busek. Three performance profiles were demonstrated: steady state, long and short duration pulses. For operating the thruster, there is a catalyst pre-heat requirement of 12 W for about eight minutes. In addition, the thruster is combined with a piezo-actuated micro-valve that is suitable for long-term propellant compatibility. While integrated system testing of the thruster and microvalve have occurred, further development is required before raising the TRL of the integrated system. The integrated testing demonstrated minimum impulse bits of 36 mNs. A full duty cycle test of the whole system will be included in future activities (Tsay, Frongillo and Lafko, et al. 2014), but the current status is unknown.

Tethers Unlimited, Inc. is developing a water electrolysis propulsion system called HYDROS-C (Figure 4.4), which fits...
into a 1U volume and uses water as propellant. On-orbit, water is electrolyzed into oxygen and hydrogen and these propellants are combusted as in a traditional bi-propellant thruster. This thruster provides an average thrust of 1.2-N with 310 s Isp. This system has been selected for NASA’s first Pathfinder Demonstration CubeSat Mission planned for launch early 2019 (D. Messier 2018). The current TRL for this unit is 6 as it has not yet flown.

NanoAvionics has developed a non-toxic mono-propellant propulsion system called Enabling Propulsion System for Small Satellites (EPSS) which was demonstrated on LituanicaSAT-2, a 3U CubeSat, to correct orientation and attitude, avoid collisions, and extend orbital lifetime (European Space Agency 2017). It uses ADN as propellant and gives 252 s of specific impulse that is designed to provide 0.3 N thrust and up to 200 m/s delta-V. LituanicaSAT-2 was launched June 2017 and successfully separated from the primary payload (Cartosat-2) as part of the European QB50 initiative. The current TRL is 7.

A novel arc-ignition “green” CubeSat hybrid thruster system prototype is currently under development at Utah State University. This system is fueled by 3-D printed acrylonitrile butadiene styrene (ABS) plastic for its unique electrical breakdown properties. Initially, high-pressure gaseous oxygen (GOX) was to be used as the oxidizer, however after safety considerations by NASA Wallops High Pressure Safety Management Team, it was concluded the oxidizer needed to contain 60% nitrogen and only 40% oxygen. On March 25th 2018, the system was successfully tested aboard a sounding rocket launched from NASA WFF into space and the motor was successfully re-fired 5 times. During the tests, 8-N of thrust and a specific impulse of 215 s were achieved as predicted (Whitmore 2018). For small spacecraft applications, the TRL is currently 6.

Cold Gas

Cold gas systems are relatively simple systems that provide limited spacecraft propulsion and are one of the most mature technologies for small spacecraft. Thrust is produced by the expulsion of an inert, non-toxic propellant which can be stored in high pressure gas or saturated liquid forms. Warm gas systems have been used in several missions for pressurization, and use the same basic principle, yielding more specific impulse performance than cold gas.

Cold gases are suitable for small buses due to their very low grade of complexity and are inexpensive and robust. They can be used when a small total impulse is required. Primary advantages include a small impulse bit for attitude control applications and the association of small volume and low weight. Recently, new designs have improved the capability of these systems for nanosatellite buses such as 3U CubeSats. Table 4-3 shows the current state-of-the-art for cold and warm gas propulsion systems for small spacecraft.
A cold gas thruster developed by Marotta flew on the NASA ST-5 mission (launch mass 55 kg) for fine attitude adjustment maneuvers. It incorporates electronic drivers that can operate the thruster at a power of less than 1 W. It has less than 5 ms of response time and it uses gaseous nitrogen as propellant (Schappell, et al. 2005).

Surrey Satellite Technology Ltd. (SSTL) has included a butane propulsion system in several small spacecraft missions for a wide range of applications in Low Earth Orbit (LEO) and Medium Earth Orbit (MEO). In this system, propellant tanks are combined with a resistojet thruster and operation is controlled by a series of solenoid valves (Figure 4.5). It uses electrical power to heat the thruster and improve the specific impulse performance with

### Table 4-3: Cold Gas Propulsion Systems

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Thrust</th>
<th>Specific Impulse (s)</th>
<th>Propellant</th>
<th>TRL Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>MicroThruster</td>
<td>Marotta</td>
<td>0.05 – 2.36 N</td>
<td>65</td>
<td>Nitrogen</td>
<td>9</td>
</tr>
<tr>
<td>Butane Propulsion System</td>
<td>SSTL</td>
<td>0.5 N</td>
<td>80</td>
<td>Butane</td>
<td>9</td>
</tr>
<tr>
<td>Nanoprop 3U</td>
<td>GomSpace/NanoSpace</td>
<td>0.01 – 1 mN</td>
<td>*60 – 110</td>
<td>Butane</td>
<td>9</td>
</tr>
<tr>
<td>Nanoprop 6U</td>
<td>GomSpace/NanoSpace</td>
<td>4 – 40 mN</td>
<td>*60 – 110</td>
<td>Butane</td>
<td>9</td>
</tr>
<tr>
<td>MiPS Cold Gas</td>
<td>VACCO</td>
<td>53 mN</td>
<td>40</td>
<td>Butane</td>
<td>7</td>
</tr>
<tr>
<td>MarCO-A and - B MiPS</td>
<td>VACCO</td>
<td>25 mN</td>
<td>40</td>
<td>R236FA</td>
<td>9</td>
</tr>
<tr>
<td>CPOD</td>
<td>VACCO</td>
<td>10 mN</td>
<td>40</td>
<td>R236FA</td>
<td>7</td>
</tr>
<tr>
<td>POPSAT-HIP1</td>
<td>Micro Space</td>
<td>0.083 – 1.1 mN</td>
<td>32 – 43</td>
<td>Argon</td>
<td>8</td>
</tr>
<tr>
<td>CNAPS</td>
<td>UTIAS/SFL</td>
<td>12.5 – 40 mN</td>
<td>40</td>
<td>Sulfur Hexafluoride</td>
<td>9</td>
</tr>
<tr>
<td>CPOD</td>
<td>VACCO</td>
<td>25 mN</td>
<td>40</td>
<td>R134A/R236FA</td>
<td>6</td>
</tr>
</tbody>
</table>

*Information was taken from brochure and may need to be updated by vendor.

![Figure 4.5: SSTL butane propulsion system. Image courtesy of Gibbon (2010).](image-url)
respect to the cold gas mode. It has been in design for more than five years and uses a RS-422 electrical interface (Gibbon 2010).

In June 2014, Space Flight Laboratory at University of Toronto Institute for Aerospace Research (UTIAS) launched two 15 kg small spacecraft to demonstrate formation flying. The Canadian Nanosatellite Advanced Propulsion System (CNAPS), shown in Figure 4.6, consisted of four thrusters fueled with liquid sulfur hexafluoride. This non-toxic propellant was selected since it has high vapor pressure and density which is important for making a self-pressurizing system (Pauliukonis 2017). This propulsion module is a novel version of the previous NanoPS that flew in the CanX-2 mission in 2008 (Bonin, et al. 2015).

Another flight-demonstrated propulsion system was flown in the POPSAT-HIP1 CubeSat mission (launched June 2014), which was developed by Microspace Rapid Pte Ltd in Singapore. It consisted of a total of eight micro-nozzles that provided control for three rotation axes with a single-axis thrust for translational applications. The total delta-V has been estimated from laboratory data to be between 2.25 and 3.05 ms\(^{-1}\). Each thruster has 1 mN of nominal thrust by using argon propellant. An electromagnetic microvalve with a very short opening time of 1 m-s operates each thruster (Manzoni and Brama 2015).

A complete cold gas propulsion system has been developed for CubeSats with a Microelectromechanical system (MEMS) (Figure 4.7) that provides accurate thrust control with four butane propellant thrusters. While thrust is controlled in a closed loop system with magnitude readings, each thruster can provide a thrust magnitude from zero to full capacity (1 mN) with 5 μN resolution. The dry mass of the system is 0.220 kg and average power consumption is 2 W during operation (Kvell, et al. 2014). This system is based on flight-proven technology flown on larger spacecraft (PRISMA mission, launched in 2010). The MEMS cold gas system was included on the bus of the TW-1 CubeSat, launched in September 2015 (NASA STMD 2013).

The CubeSat Proximity Operations Demonstration (CPOD) is a mission led by Tyvak Nano-Satellite Systems. It incorporates a cold gas propulsion system built by VACCO Industries that provides up to 186 N-s of total impulse. This module operates at a steady state power of 5 W and delivers 40 s of specific impulse while the nominal thrust is 10 mN (VACCO Industries 2015). It uses self-pressurizing refrigerant R236fa propellant to fire a total of eight thrusters distributed in pairs at the four corners of the module. It has gone through extensive testing at the US Air Force Research Lab. Endurance tests consisted of more than 70,000 firings (Bowen, Villa and Williams 2015).

**Solid Motors**

Solid rocket technology is typically used for impulsive maneuvers such as orbit insertion or quick de-orbiting. Due to the solid propellant, they achieve moderate specific impulses and high thrust magnitudes that are compact and suitable for small buses. There are some electrically controlled solid thrusters that operate in the mN range. These are restartable, have steering capabilities and
are suitable for small spacecraft applications, unlike larger spacecraft systems that provided too much acceleration. Table 4-4 shows the current state-of-the-art in solid motors for small spacecraft. These thrust vector control systems can be coupled with existing solid rocket motors to provide controllable high delta-V in relatively short time. A flight campaign tested the ability of these systems to effectively control the attitude of small rocket vehicles. Some of these tests were performed by using state-of-the-art solid rocket motors such as the ISP 30 s developed by Industrial Solid Propulsion (Zondervan, et al. 2014).

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Total Mass (kg)</th>
<th>Average Thrust (N)</th>
<th>Specific Impulse (s)</th>
<th>TRL Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISP 30 sec motor</td>
<td>Industrial Solid Propulsion</td>
<td>0.95</td>
<td>37</td>
<td>187</td>
<td>6</td>
</tr>
<tr>
<td>STAR 4G</td>
<td>Northrop Grumman Innovation Systems</td>
<td>1.5</td>
<td>258</td>
<td>277</td>
<td>6</td>
</tr>
<tr>
<td>CAPS-3</td>
<td>DSSP</td>
<td>2.33</td>
<td>0.3</td>
<td>&lt;300</td>
<td>8</td>
</tr>
<tr>
<td>MAP</td>
<td>PacSci EMC</td>
<td>Customized</td>
<td>N/A</td>
<td>210</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4-4: Solid Rocket Motors

SPINSAT, a 57 kg spacecraft, was deployed from ISS in 2014 and incorporated a set of first-generation solid motors, the CubeSat Agile Propulsion System (Figure 4.8) which was part of the attitude control system developed by Digital Solid State Propulsion LLC (DSSP). The system was based on a set of Electrically-controlled Solid Propellant (ESP) thrusters that consist of two coaxial electrodes separated by a thin layer of electric solid propellant. This material is highly energetic but non-pyrotechnic and is only ignited if an electric current is applied. The thrust duration can be better controlled, and allows for better burn control, and the lack of moving parts make the system suitable for small spacecraft.

The STAR motor was initially developed and tested for deploying constellations of small spacecraft in early 2000 under a NASA Goddard Space Flight Center program. The 4G motor was first tested in late 2000 (Nothrup Grumman Innovation Systems 2018), but the current status of this motor is unknown.

Electric Propulsion Systems

Electric propulsion has experienced significant improvement in terms of systems available and component maturity. For many small spacecraft concepts, high specific impulses are necessary to comply with delta-V budgets. Depending on thruster technology, specific impulses for electric propulsion can range between 700-3000 s. However, thrust is low meaning long maneuver times.
Some thrusters are more suitable for small correction maneuvers and attitude control applications due to low impulse bits while others are designed to achieve high accelerations for interplanetary spiral trajectories. A wide spectrum of propellants is offered with electric propulsion. Iodine is proposed for some technologies due to its very high density that allows for higher delta-V maneuvers for necessary transfer trajectories. For smaller delta-V applications, solid-state materials such as polytetrafluoroethylene (PTFE)--or Teflon--are used in most Pulsed Plasma Thrusters (PPTs), while electrosprays use various forms of ionic liquid.

**Resistojets**

Resistojets are the simplest form of electric propulsion. Thrust is produced by electrically heating the propellant so that the resulting gas can be expanded and expelled at high velocity out of the nozzle. Table 4-5 lists the current state-of-the-art for Resistojet designs that are applicable to small spacecraft.

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Thrust (N)</th>
<th>Power (W)</th>
<th>Specific Impulse (s)</th>
<th>TRL Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Resistojet</td>
<td>Busek</td>
<td>10 mN</td>
<td>15</td>
<td>150</td>
<td>5</td>
</tr>
<tr>
<td>CHIPS</td>
<td>CU Aerospace and VACCO</td>
<td>30 mN</td>
<td>30</td>
<td>82</td>
<td>5</td>
</tr>
<tr>
<td>PUC</td>
<td>CU Aerospace and VACCO</td>
<td>0.45</td>
<td>15</td>
<td>70</td>
<td>6</td>
</tr>
<tr>
<td>Resistojet Propulsion System</td>
<td>SSTL</td>
<td>100 mN</td>
<td>30 - 50</td>
<td>48 - 99</td>
<td>9</td>
</tr>
</tbody>
</table>

The Micro Resistojet offered by Busek is still in development for small spacecraft, but current specs list a max of 10 mN thrust at 150 s Isp at 15 W of power. The delta-V capability for a 4 kg spacecraft was projected at 60 m/s, and the total system mass is 1.25 kg when using ammonia as the propellant. The current status of this thruster is unknown.

Surrey Satellite Technology Ltd. (SSTL) has developed a resistojet propulsion system that has flown in several missions. It can work with different types of propellant such as xenon, butane or nitrogen. Thrust can be up to 100 mN and the specific impulse varies with the selected propellant ranging from 48 s for xenon to 99 s for nitrogen. The system uses power from 30 to 50 W and does not require a PPU since it works directly from the bus voltage input. There is heritage on small spacecraft, so is not scalable on a CubeSat without redesign.

CU Aerospace and VACCO have built a Propulsion Unit for CubeSats (PUC) (Figure 4.9). It consists of a fully integrated system that includes a controller, PPU, valves, sensors and a Micro-Cavity Discharge (MCD) thruster. High density and self-pressurizing liquids are used as propellants.
propellants by using the MCD heating technology together with an optimized low mass flow nozzle (Carroll, et al. 2015).

CU Aerospace and VACCO Industries have also developed a CubeSat High Impulse Propulsion System (CHIPS). This module incorporates a main micro-resistojet plus four equally distributed cold gas thrusters acting as a 3-axis attitude control system. By leveraging VACCO’s compact friction-less valve technology and using an inert, non-toxic R-134a propellant, this system achieves a high total impulse to volume ratio. It occupies a 1U+ space in order to target 2U and 6U spacecraft buses. A fully integrated system with flow and power control has been demonstrated at the Electric Propulsion Laboratory at the University of Urbana-Champaign, Illinois. Tests included thrust and specific impulse measurements that estimated 82 s for the warm fire mode and 47 s for the cold fire mode. It can provide up to 563 N-s of total impulse, and a throttleable thrust of 30 mN in warm fire mode for primary propulsion. The cold gas mode is used for three axis attitude control and provides 323 N-s of total impulse and 19 mN of thrust. The TRL of the integrated system is 5, with a second phase currently in development (Hejmanowski, et al. 2015).

Busek Co, Inc. has leveraged previous flight and design efforts to miniaturize fundamental components such as valves and PPU’s for a micro-resistojet. This system uses non-toxic ammonia propellant and delivers a total impulse of 404 N-s for main delta-V applications and 23 N-s for the ACS (Busek Co. Inc. 2015).

The University of Toronto Institute for Aerospace Studies has also developed a warm gas resistojet system that has been assessed at TRL 6. This propulsion system was supposed to fly on the LEO 2 spacecraft to achieve flight heritage on November 28, 2017, but failed due to a launch vehicle anomaly (UTIAS-SFL 2018). Additionally, UTIAS-SFL developed a nitrous oxide (N₂O) fueled monopropulsion system that provided 100 mN thrust at 131 s Isp during environmental tests performed in 2016 (Tarantini, et al. 2016). N₂O is a common oxidizer for hybrid systems that can be safely stored and readily decomposes into breathable air. Current status is unknown.

**Electrosprays**

Electrospray propulsion systems use the principle of electrostatic extraction and acceleration of ions from a propellant consisting of a negligible vapor pressure conductive salt. One of the biggest advantages of this technology with respect to other traditional electric propulsion systems is that no gas-phase ionization is required. The propellant does not need to be pressurized for storage since it flows via capillary action due to the ion evaporation process. The emission can be controlled by modulation of the voltage input in a closed loop feedback system with current measurements. In some cases, both species of negative and positive ions can be used, avoiding the need for a neutralizer which may be key to the design and operation of the system. Expelled ions achieve very high velocities, which translates into high specific impulses. Typically, the most widely used propellant in electrosprays is the ionic liquid 1-Ethyl-3-Methyl-Imidazolium Tetrafluoroborate (EMI-BF4). NASA’s Advanced In-Space Propulsion (AISP) project has created a portfolio that includes the development of Microfluidic Electrospray Propulsion (MEP). Table 4-6 displays the current state-of-the-art for small spacecraft applicable electrospray thrusters.
Electrospray technology has significantly advanced at Massachusetts Institute of Technology (MIT) Space Propulsion Laboratory (SPL), and some companies have started to commercialize systems based on this effort (Figure 4.10). Voltage versus current curves, and time of flight spectroscopy, among other tests, have helped to understand the ionic and electrical characteristics of the thruster. MIT has demonstrated a total of 315 hours of continuous electrospray operation, where a magnetically levitated thrust balance was used to measure thrust (Mier-Hicks and Lozano 2015). Each thruster has a total of 480 emitters, a passive propellant management system that includes a 1.2 cm³ tank, and an acceleration chamber. At the system level, MIT has developed the Scalable Ion Electrospray Propulsion System (S-iEPS, Figure 4.11), that features a total of eight thrusters that fire along a single axis. This module is able to provide 74 μN and more than 1160 s of specific impulse with a power draw of less than 1.5 W. It is lightweight, about 0.095 kg including PPU, and fits in a 0.2U volume (Krejci, et al. 2015). The S-iEPS thruster was going to be integrated on the Aerocube 8 CubeSat mission launched November, 2016, from Vandenberg on an Atlas V (Akpan 2018), however because there is no documentation indicating that this thruster operated successfully, the TRL was assessed at 6.

Table 4-6: Electrospray Propulsion Systems

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Thrust</th>
<th>Power (W)</th>
<th>Specific Impulse (s)</th>
<th>TRL Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-iEPS</td>
<td>MIT</td>
<td>74 µN</td>
<td>1.5</td>
<td>1160</td>
<td>6</td>
</tr>
<tr>
<td>TILE-5000</td>
<td>Accion Systems Inc.</td>
<td>1.5</td>
<td>8-25</td>
<td>1250</td>
<td>5</td>
</tr>
<tr>
<td>1 mN Electrospray</td>
<td>Busek</td>
<td>0.7 mN</td>
<td>15</td>
<td>800</td>
<td>7</td>
</tr>
<tr>
<td>100μ</td>
<td>Busek</td>
<td>0.1 mN</td>
<td>5</td>
<td>2300</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 4.10: Electrospray thruster. Image courtesy of MIT SPL.

Figure 4.11: S-iEPS propulsion system. Image courtesy of MIT SPL.
Busek Inc. has developed fully integrated electrospray propulsion systems in the mN range, the 100 micro-Newton BET 100uN and the one milli-Newton BET-1mN. These modules include a propellant-less cathode neutralizer and a low pressure customizable tank that were leveraged from the module incorporated into the NASA ST-7/ESA LISA Pathfinder spacecraft that launched in December, 2015, where all eight electric propulsion systems successfully fired (Busek 2016). The 1mN system uses 15 W of power and provides 675 N-s with 50 mL of propellant and has a mass of 1.15 kg, whereas the 100 μN class thruster provides a specific impulse of 2300 s and consumes 5 W. The 100 μN can deliver 85 ms\(^{-1}\) to a 4 kg CubeSat with a wet mass of 0.320 kg, using 10 mL of an ionic liquid propellant that has been fully characterized during the ST-7 flight program (Busek Co. Inc. 2015). The BET-100 systems was selected in March, 2016, to fly on a NASA Ames Pathfinder Technology Demonstration mission that is scheduled for launch in 2019 and underwent quality testing in late 2017. However this flight has been cancelled and there is no current information on this system.

The Micro Devices Laboratory (MDL) at the Jet Propulsion Laboratory (JPL) has developed a highly integrated and scalable indium MEP system (Figure 4.12) that has a dry mass of less than 0.010 kg and provides thrust in the 20-100 μN range. Indium metal is stored in solid form and heated afterwards to be used as propellant. Over 10 hours of continuous operation tested an initial prototype assembly (JPL 2013), but the current TRL for this system is unknown.

**Ion Engines**

In ion thrusters, propellant is ionized using various plasma generation techniques. Radio Frequency (RF) engines achieve thrust by producing ions with electrode-less inductive discharges that are typically achieved using a helical coil at frequencies in the range of 1 MHz. The particles are then accelerated at very high exhaust velocities by electrostatic grids. These devices have a high efficiency when compared to other electric propulsion systems at lower thrust. In addition, the absence of electrodes avoids potential threats to thruster lifetime, which is only limited by grid erosion. Table 4-7 displays the current state-of-the-art in ion engines for small spacecraft.

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Thrust</th>
<th>Power (W)</th>
<th>Specific Impulse (s)</th>
<th>Propellant</th>
<th>TRL Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIT-3</td>
<td>Busek</td>
<td>1.4 mN</td>
<td>60</td>
<td>3500</td>
<td>Iodine</td>
<td>5</td>
</tr>
<tr>
<td>1-COUPS</td>
<td>University of Tokyo</td>
<td>0.3 mN</td>
<td>N/A</td>
<td>1000</td>
<td>Xenon</td>
<td>7</td>
</tr>
<tr>
<td>RIT-μX</td>
<td>Airbus</td>
<td>50 – 500 μN</td>
<td>50</td>
<td>300 – 3000</td>
<td>Xenon</td>
<td>5</td>
</tr>
<tr>
<td>IFM Nano Thruster</td>
<td>Enpulsion</td>
<td>10 μN – 0.4 mN</td>
<td>40</td>
<td>2000- 6000</td>
<td>Indium</td>
<td>7</td>
</tr>
</tbody>
</table>
Busek is developing a RF ion thruster that can operate with both xenon and iodine propellants, achieving similar performances (Tsay, Frongillo and Hohman, Iodine-Fueled Mini RF Ion Thruster for CubeSat Applications 2015). The BIT-3 engine has 3 cm diameter grids and is capable of providing variable specific impulse and thrust. At 60 W of operating power, it can achieve an efficiency of 35%. In 2015, it was shown that the test performance results on the iodine version have shown that thrust-to-power ratios are similar to the ones achieved with xenon as propellant. Complementary technologies associated with the thruster (such as propellant tanks and feed systems), have also been demonstrated for this propellant. The thrusters are compatible with iodine since the plasma-generation chambers in RF engines are generally built with ceramic materials that are resistant to corrosion. In July, 2017, the BIT-3 completed two critical design reviews for upcoming small spacecraft missions IceCube and LunaH-Map, which are scheduled to be launched with EM-1 in 2020 (Busek 2017).

Recently, the Japanese Proximate Object Close flyby with Optical Navigation (PROCYON) mission has shown successful operation of a propulsion system in space. The Ion thruster and Cold-gas thruster Unified Propulsion System (I-COUPS) was designed at the University of Tokyo and is an integrated system comprised of two sets of ion and cold gas thrusters. Both technologies share the same gas feed system that provides xenon propellant. This combines high thrust and large delta-V capabilities. Cold gas thrusters are used for reaction wheel de-saturation and small correction burns, while ion engines are kept for deep space maneuvers. In total, the mass of the propulsion system is less than 10 kg, including propellant. The ion engines in the I-COUPS unit are an evolution of the Miniature Ion Propulsion System (MIPS), which was previously launched on board the Hodoyoshi-3/4 mission in October, 2014. This spacecraft was placed on a Sun synchronous orbit and had a mass of 65 kg. The MIPS had a wet mass of 8.1 kg with 1 kg of propellant mass. Ion thruster operation was proven by providing continuous acceleration (Takegahara, et al. 2015).

Airbus offers a family of RF ion thrusters and their smallest is the RIT-μX (Figure 4.13). This thruster is designed for small spacecraft buses and high precision maneuvers. Various thrust configurations were proposed and tested. It uses xenon as propellant and it has a dry mass of 0.440 kg. In 2013, a system in the 50-500 μN range was demonstrated and thrust resolution, linearity, response and noise met LISA Pathfinder mission requirements, increasing the TRL to 5. The nominal power to open rate is less than 50 W and the specific impulse is between 300 and 3000 s, depending on the configuration. The maximum demonstrated specific impulse was 3500 s and high thrust levels of 50-2500μN were established in 2015 (Leiter, et al. 2015). Current status is unknown.

The field-emission electric propulsion (FEEP) device is a type of ion thruster that uses liquid metal rather than gases like xenon as propellant. Currently Enpulsion is the only commercial manufacturer in the world offering an FEEP thruster. The instantaneous frequency measurement (IFM) Nano Thruster fits in a 1U volume and can produce 220 mN of thrust with a specific impulse of 4,000 seconds, and has already been flown on a 3U nanosatellite, deployed in January, 2018 (Foust 2018).
Pulsed Plasma and Vacuum Arc Thrusters

In Pulsed Plasma Thrusters (PPTs), thrust is produced by triggering a high voltage discharge between two electrodes that results in an electric arc that typically ablates a solid-state material like PTFE (Teflon). A self-generated magnetic field is produced which accelerates and expels particles from the thruster head, while the propellant is typically pushed forward by a spring as it is consumed. This technology has significant heritage from larger spacecraft, and due to its simplicity, miniaturization was easier than other electric propulsion systems. Major problems such as short circuits or non-uniform propellant ablation are under active research.

These systems are suitable for attitude control and fine pointing applications since the trigger pulse of the discharge can be adjusted, small impulse bits allow for high precision. Typically, the propulsion system consists of just a PPU that controls the discharge to operate the thrusters. The energy is stored in a capacitor bank which accounts for a significant portion of the system mass. Various materials have been tested for PPT use, however PTFE is the industry standard. Table 4-8 lists the current state-of-the-art for small spacecraft PPT thrusters.

<table>
<thead>
<tr>
<th>Table 4-8: Pulsed Plasma and Vacuum Arc Propulsion Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product</strong></td>
</tr>
<tr>
<td>PPTCUP</td>
</tr>
<tr>
<td>NanoSat PPT</td>
</tr>
<tr>
<td>μ-CAT</td>
</tr>
<tr>
<td>BmP-220</td>
</tr>
<tr>
<td>MPACS</td>
</tr>
<tr>
<td>Metal Plasma Thruster</td>
</tr>
</tbody>
</table>
Mars Space Ltd. and AAC-Clyde have developed a compact propulsion module (Figure 4.14) specifically designed to provide maneuvering capabilities to CubeSats. At the University of Southampton, thermal cycling, vibration, Electro Magnetic Compatibility (EMC) and lifetime tests were performed. Vibration test results showed that the module sustains the mechanical vibrations during launch and the Electro-Magnetic (EM) noise levels during discharge were mostly compliant with guidelines. The system has a total mass of 0.270 kg and is characterized by an average specific impulse of 655 s and a total impulse of 48.2 Ns. It has a single thruster that uses PTFE propellant and is side-fed to maximize discharge length, with an electrode design that minimizes carbonization (Ciaralli, Coletti and Gabriel 2015).

Busek has extensive experience in developing PPT systems. Their Micro Pulsed Plasma Altitude Control System (MPCAS) flew on the FalconSat-3 mission in 2007. This module consisted of eight thrusters and provided attitude control with precise impulse bits of 80 μN-s at a moderate power of less than 10 W (France, Anthony and Hart 2011) by using PTFE propellant. The system had heritage from previous investigations conducted at the Air Force Research Laboratory (AFRL) and has been evolving since this first approach, making it TRL 7. The BmP-220 is the latest version of the Busek PPT family (Figure 4.15). It has a volume of 0.7U and can provide up to 220 N-s of total impulse with 0.040 kg of propellant. An innovative solid-state switching technology enables the implementation of several emitters in a single unit. The specific impulse is 536 s and the minimum impulse bit is 0.02 mN-s (Busek Co. Inc. 2015). The system TRL is estimated to be 5.

Dr. Patrick Neumann is developing a Pulsed Cathodic Arc Thruster (PCAT), or Neumann Drive, that boasts a specific impulse as high as 14,000 seconds. It has broken the record for specific impulse previously held by NASA’s HiPEP thruster. This thruster operates like an arc welder, where metal is heated as arcing current jumps between a cathode and an anode. As electrons jump, they carry some atoms with them in the form of plasma and these atoms are propelled into space, creating thrust. This ion drive will be installed on the Airbus Defense and Space Bartolomeo platform as part of the FAST (Facility for Australian Space Testing) mission in mid-2019 (Science Alert 2016).

Vacuum arc thrusters are another type of plasma-based propulsion device that produces thrust by propellant ionization. This technology consists of two metallic electrodes separated by a dielectric insulator. One of them is used as solid metallic propellant and is consumed as the thruster operates. Advantages of using a metallic solid propellant over the more traditional option of PTFE are a lower energy consumption per ionized mass, high pulse stability, and higher repetition rates due to the thermal properties of metals.

The Micro-Cathode Arc Thruster (μCAT) developed by George Washington University (GWU), uses vacuum discharges to ablate the cathode material. It consists of a 5 mm thruster head that contains a concentrically-aligned and cylindrically-shaped anode, cathode and insulator. By
sending a pulse created by the PPU to the electrode interface, a high voltage arc is produced across it (Keidar, Zhuang and Shashurin, Electric propulsion for small satellites. 2015). The μCAT offers a quasi-perfect ionization degree of the plasma particles in the exhaust plume, giving a near zero back flux. This propulsion technology generates thrust by consuming cathode material made of titanium with a high voltage vacuum arc, producing highly ionized plasma jets with high exhaust velocities. In addition, the incorporation of an external magnetic coil improves significantly the capabilities of the thruster (Keidar, Haque, et al. 2013).

An autonomous and modular micro electric propulsion system based on this technology has been designed and built at NASA Ames Research Center in partnership with GWU. This module fits into a 0.2U volume and consists of one Printed Circuit Board (PCB) that commands and operates up to four vacuum arc thrusters. Two PPUs, implemented in the main PCB, create the necessary discharges to operate the thruster. An average thrust in the μN range is controlled by selecting different thrusting frequencies. This system was tested and measured in relevant vacuum conditions at NASA Glenn Research Center on a high-accuracy torsional thrust stand.

Furthermore, a partnership between GWU and the United States Naval Academy resulted in the integration of a μCAT propulsion system into the Ballistically Reinforced Communication Satellite (BRICSAT). This mission was launched in May of 2015 and consisted of four PPUs operating four thrusters in total. Preliminary retrieved data has shown that the system successfully accomplished the objective of detumbling the spacecraft. After two days, the propulsion system was able to reduce the initial tumbling from 30°s⁻¹ to nearly 1.5°s⁻¹, increasing the TRL of this system from 6 to 7 (Hurley, et al. 2015).

**Hall Effect Thrusters**

Hall Effect propulsion is a mature technology for large spacecraft systems (Figure 4.16). Miniaturization of some of the components, such as neutralizers, is complicated to achieve, and power consumption is relatively high compared to other electric propulsion technologies. However, improvements in integrating complete Hall Effect propulsion systems can potentially support large transfers for interplanetary missions. See Table 4-9 for current state-of-the-art technology in Hall Effect Thrusters for small spacecraft.

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Thrust (mN)</th>
<th>Power (W)</th>
<th>Specific Impulse (s)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHT-200</td>
<td>Busek</td>
<td>13</td>
<td>200</td>
<td>1390</td>
<td>Xenon TRL 8, Iodine TRL 4</td>
</tr>
<tr>
<td>HT100</td>
<td>SITAEI</td>
<td>5 – 15</td>
<td>175</td>
<td>&lt;1350</td>
<td>Xenon TRL 6</td>
</tr>
<tr>
<td>CHT</td>
<td>UTIAS SFL</td>
<td>6.2</td>
<td>200</td>
<td>1139</td>
<td>Xenon TRL 6</td>
</tr>
</tbody>
</table>

Busek has developed a complete Hall Effect thruster propulsion system for small spacecraft. The BHT-200 (Figure 4.16) is best suited for small spacecraft buses of relatively high mass and power supply since it needs 100-300 W to operate. This system has flight heritage from the 2006 TacSat-2 mission, and was part of the payload in the FalconSat-5 mission in 2010. Additionally, it was launched with the FalconSat-6 (150 kg) mission on a Falcon Heavy in 2018. This model can
operate with multiple propellants (Busek Co. Inc. 2015). The use of iodine will advance the technology due to its increased density over xenon and its lower operating pressure, which reduces cost and risk. More details can be found in the "On the Horizon" section.

The HT100, developed by Sitael Aerospace, has been extensively tested through campaigns that include characterization under thermal-vacuum conditions and structural analysis under heavy loads. Cathode erosion has been observed in an endurance test that lasted for 1650 hours where no thermal problems or important performance reduction was observed. The nominal operating power at 175 W gives a thrust range of 5-15 mN. The thruster mass is 0.440 kg, it uses xenon as propellant, and it can achieve a peak total efficiency of up to 35% and a maximum specific impulse of 1350 s. The HT100 has been selected for an in-orbit validation program by the European and Italian space agencies, where accelerated reentry and orbital maintenance will be tested. A larger version, the HT400, operates at a nominal power of 400 W and is at TRL 5 (Misuri, et al. 2015).

The Space Flight Laboratory (SFL) at the University of Toronto is developing a low power cylindrical Hall thruster (Figure 4.17) that operates below 200 W and has a 26 mm diameter ionization chamber. The cylindrical geometry of the ionization chamber was chosen in order to overcome the challenges of the annular chamber of traditional Hall thrusters. With this configuration, better efficiencies can be achieved while maintaining a sufficient thrust magnitude between 2.5-12 mN. Annular ionization chambers are mechanically simpler and produce high thrust to power ratios that are beneficial for small spacecraft applications. However, the efficiency still gets reduced when the chamber is redesigned to optimize low power operation.

Excluding the cathode, the weight of the first prototype was 1.6 kg. This device went under magnetic characterization and performance tests in vacuum. It uses xenon as a baseline propellant due to its improved performance over other gases such as argon. Further testing and design modifications were done in order to raise the TRL from 5 to 6 in 2016 (Pigeon and Zee. 2015). Current status is unknown.

Radio Frequency (RF) Thrusters

The Phase Four RF Thrusters (RFT) leverage ambipolar technology developed from the CubeSat Ambipolar Thruster (CAT), and have been tested at The Aerospace Corporation and Phase Four laboratories. Similar to its predecessor, the RFT has a ceramic plasma liner which is wrapped in an inductive RF antenna coil that is itself located inside a magnetic field generated by a permanent magnet. Inside the liner, xenon is ionized and the subsequent plasma is heated by induced oscillating magnetic fields. Electrons get accelerated at very high energies and this quick flux produces a charge imbalance in the system. Then, propellant ions are expelled out of the nozzle due to the momentary imbalance, becoming the main source of thrust.

There are several notable advantages of the RFT: the size reduction and power density improvements in the RF switching electronics have allowed the PPU to weigh less than 500 g for
LEO CubeSat applications; second, the ambipolar nature of the technology obviates the need for a cathode neutralizer, which implies that no high voltage electronics are required; finally, since the thruster does not have electrodes, more propellants can be used, since they are no longer corrosive to cathodes or anodes in their plasma state.

There have been proof of concept Phase Four RF thrusters, RFT-0 RFT-2 and RFT-X, that showed comparable performance on a direct thrust stand to other RF thrusters that operate at much higher powers or have higher dimensions and mass (U. M. Siddiqui 2017). Despite the differences in the electrical, mechanical and magnetic characteristics, the specific impulse performance results scaled to the same linear trend, and are in the same order of magnitude as equivalent low power Hall Effect thrusters, within 50% of the thrust output at similar power levels, and with the advantage of being electrodeless (Siddiqui and Cre tel 2018). Based on these technologies, the Maxwell RF Thruster propulsion system corresponds to a 400 W class engine, and it is operated at a power range of 342-480 W, achieving 4.3-9 mN at specific impulses of 1463-918 s (Phase Four Inc. 2018). The TRL on the Maxwell thruster is currently 5.

**Propellant-less Systems**

Systems that do not carry propellant for thrust generation are ideal candidates for small spacecraft. Such systems avoid complexity and reduce mass limitations, and can achieve high accelerations that can potentially propel an object for interplanetary travel.

Solar sails are the most popular method of propellant-less propulsion. They take advantage of solar radiation pressure by reflecting photons on a large sail made of a highly reflective material. Several missions have been conducted to demonstrate this technology for large buses such as the Japanese IKAROS, launched in 2010. Regarding small spacecraft, NASA has been conducting extensive research that resulted in the launch in 2010 of NanoSail-D2, a technology demonstration mission managed and designed by NASA Ames Research Center and NASA Marshall Space Flight Center. The sail had a deployed surface area of 10 m², was made of a thin highly reflective material called CP-1, and weighed 4.2 kg (Alhorn, et al. 2011).

One of the most recent solar sail missions for small spacecraft was performed by the Planetary Society in 2015. The 3U LightSail-1 spacecraft completed its technology demonstration test in Space by fully deploying a solar sail in LEO. The dimensions were 5.6 m on a side and 32 m² of total area once deployed. In 2018, a follow up mission called LightSail-2 that will be housed on 3U Prox-1, will demonstrate orbit raising maneuvers using the same 32 m² of mylar sail at a circular 720 km orbit as part of the Space Test Program (SPT-2). This spacecraft will fly on a Falcon heavy rocket to an approximately 720 km LEO orbit, where an orbital change in altitude or inclination will be performed (Ridenoure, et al. 2015).

**On the Horizon**

More small spacecraft missions will incorporate propulsion systems as propulsion technology matures, allowing for more complex mission architectures. This section will cover near-term spacecraft with propulsion, as well as promising technologies that will become important propulsion assets for future missions.

A smaller thruster version of just 1 cm grids, called the BIT-1, is also under development by Busek. This system has a mass of 0.053 kg, provides 100 μN thrust and 2150 s Isp with 10W of power; thrust can exceed 180 μN and 3200 s Isp when more power is available (Busek 2014). As of 2015 the TRL was assessed at 4, however current status is unknown.
There are several other propulsion technologies currently being developed: Ventions LLC is working on an integrated 3U CubeSat propulsion system using non-toxic propellant; hybrid non-toxic/cold gas propulsion system for 6U and 12U spacecraft by Planetary Resources Development Corporation; and a non-toxic solid rocket for CubeSats that allows for second ignition and uses an aluminized version of an Electric Solid Propellant (ESP) from Digital Solid State Propulsion (DSSP). Because ESPs are electrically ignited, they are safer than traditional solid energetic propellants (NASA 2018).

Orbital Technologies Corporation (ORBITEC) is developing the Miniature Nontoxic Oxide-Propane (MINNOP) propulsion system for small spacecraft which uses nitrous oxide as the oxidizer. It consists of a bipropellant system that provides a significant increase in specific impulse performance with respect to hydrazine systems when used in bi-propellant mode, with small levels of minimum impulse bit when used in cold gas mode. In 2014, a demonstration of the bipropellant thrust chamber and ignition system was performed within suitable weight constraints to fit into a 1U form factor (NASA 2018), although the current development status is unknown.

The Inductively Coupled Electromagnetic (ICE) thruster is a novel technology that is being developed by MSNW LLC. This system uses a small integrated RF oscillator to generate plasma. One of the main advantages of this system is that it can use virtually any liquid propellant. The total volume of the thruster and the PPU was expected to be less than 0.125 U, and anticipated operating power was 10-50 W. In 2015, the goal was to achieve TRL 4, however the current status is unknown.

In 2015, an experimental characterization of a low power helicon thruster was performed at Stanford University’s Plasma Physics Laboratory. Tests were conducted using water and argon propellants, and thrust was observed at various performance levels with magnitudes of 2-5 μN. Future development efforts include optimization for greater performance and thrust stand measurements (Biggs, et al. 2015). Power has been a significant hurdle in advancing this technology, so current efforts have been focused on developing a dc-RF power supply with substantial improvements in weight to power density (Liang, et al. 2017).

Princeton Plasma Physics Laboratory, with The Aerospace Corporation, have tested the performance of a small cylindrical Hall thruster with permanent magnets. The measured thrust was in the 3-6.5 mN range with a specific impulse of 1000-1900 s. Efficiency studies at a discharge voltage of 300 V achieved a maximum thruster efficiency of over 20%. This version demonstrated superior performance than another version that uses electromagnets coils (Spektor, et al. 2011). There is still ongoing research for potential solutions for this design and this thruster has a TRL of 3.

D-Orbit is designing a modular micro-propulsion system called FENIX to raise or lower CubeSats into different orbits (Figure 4.18). This system consists of four small solid rocket motors that can be configured to any size CubeSat. The capabilities of this system can boost CubeSats into a higher orbit after deployment or be used for decommissioning maneuvers. The assessed TRL of this system is currently 4 (Yost 2018).

The B125 Propulsion System is a prototype being studied at Benchmark Space Systems. The bipropellant is hydrogen peroxide (H2O2) as the oxidizer and is fueled by 2-propanol (an alcohol blend). Studies published in 2018 identified a benefit when using a homogenous catalysis process.
in that it provides the ability to operate in two modes: pseudo-monopropellant and bipropellant. The different modes are achieved by varying the flow rates of the catalyst solution and hydrogen peroxide, however developing an effective and reliable catalytic bed is still a technology challenge (Gagne, McDevitt and Hitt 2018). This system provides 1.25 N of thrust at 260 s specific impulse, and with a total mass of 1.5 kg it can provide an 8 kg nanosatellite 145 m/s of delta-V (Benchmark Systems 2017).

**Future Small Spacecraft Missions with Propulsion**

Due to significant improvements in propulsion technologies, mission concepts that were previously limited to large spacecraft are now possible with small buses. Interplanetary missions are becoming less costly, and therefore several institutions are assuming more risks to perform science missions with higher payoffs. As an example, NASA’s Exploration Mission-1 (EM-1) will provide secondary payload opportunities for up to eleven 6U CubeSats, with a mission trajectory that will provide access to deep space or lunar orbit.

NASA Ames and Glenn Research Centers are working on the Pathfinder Technology Demonstration (PTD) project which consists of a series of 6U CubeSats that will be launched to test the performance of new subsystem technologies in orbit. For the first flight version, PDT-1, the HYDROS-C water-based propellant thruster, will be demonstrated to change the spacecraft’s velocity and altitude (D. Messier 2018).

JPL is supporting the InSight mission, launched in March, 2018, which incorporated two identical CubeSats as part of the Mars Cube One (MarCO) technology demonstration. These spacecraft performed five Trajectory Correction Maneuvers (TCMs) during the mission to Mars. The CubeSats included an integrated propulsion system developed by VACCO Industries, which contained four thrusters for attitude control and another four for TCMs. The module uses cold gas refrigerant R-236FA as propellant, produces 755 N-s of total impulse, and weighs 3.49 kg (Klesh and Krajewski, MarCO: CubeSats to Mars in 2016. 2015).

A team at Purdue University and NASA Goddard Space Flight Center is developing the Film Evaporation MEMS Tunable Array (FEMTA). This Microelectromechanical systems (MEMS) thruster uses deionized liquid water as propellant with nozzles that produce thrust by applying local heat to a propellant capillary interface. Not having any mechanisms that require power is advantageous, allowing the system to operate with a low power consumption on the order of a mW. This technology will achieve TRL 6 by the end of fiscal year 2019 if technology maturation activities can achieve payload requirements for a Pathfinder Technology Demonstration 6U mission (Fowee, et al. 2017).

NEA Scout and Lunar Flashlight are two NASA MSFC missions that are going to be launched as part of EM-1, scheduled for 2020. For its main propulsion system, NEA Scout will deploy a sail of 80 m² of area with 0.0601 m/s² of characteristic acceleration, and will be steered by active mass translation via a VACCO cold gas MiPS (R236FA propellant). This module is approximately 2U in volume and will use six 23 mN thrusters to provide 30 m/s of delta-V (VACCO 2016). The propulsion system on Lunar Flashlight is a VACCO green mono propellant MiPS (AND propellant), that will be used for station keeping and attitude control. The VACCO Lunar Flashlight MiPS is approximately 3U in volume and uses four Bradford/ECAPS 100 mN thrusters which provide 3,320 N-sec of total impulse and 237 m/s delta-V (VACCO 2016).

**Summary**

A variety of propulsion technologies are currently available for small spacecraft. While cold gas and pulsed plasma thrusters present an ideal option for attitude control applications, they have
limitations for more ambitious maneuvers such as large orbital transfers. Other alternatives such as hydrazine, non-toxic propellants, and solid motors provide a high capability and are suitable for medium size buses and missions that require higher delta-V budgets. Some spacecraft have already flown with these systems or are scheduled to fly in the next year. For the near future, the focus is placed on non-toxic propellants that avoid safety and operational complications, and provide sufficient density and specific impulse despite high cost per kg. The application of this technology in CubeSats is still in development, as some of the components need to be scaled down to comply with volume, power, and mass constraints.

Electrosprays, Hall Effect thrusters and ion engines are in development, and active testing and technology demonstrations are expected for different bus sizes. These propulsion technologies will allow spacecraft to achieve very high delta-V and, therefore, to perform interplanetary transfers with low thrust.

Several other technologies, as well as new versions of existing systems with improved capabilities, are being proposed and a wide range of mature options in the following years are forecasted. As the industry progresses and more launches are scheduled, more propulsion systems will be included on board small spacecraft, increasing the average TRL for this important subsystem.

For Feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

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