

Electric Propellant Solid Rocket Motor Thruster Results Enabling Small Satellites

Frederick B. Koehler, Mark T. Langhenry, Matt H. Summers, James K. Villarreal, Thomas W. Villarreal,
Raytheon Missile Systems Tucson, Arizona, 520-545-9378, koehler@raytheon.com

ABSTRACT

Raytheon Missile Systems has developed and tested true on/off/restart solid propellant thrusters which are controlled only by electrical current. This new patented class of energetic rocket propellant is safe, controllable and simple. The range of applications for this game changing technology includes attitude control systems and a safe alternative to higher impulse space satellite thrusters. Described herein are descriptions and performance data for several small electric propellant solid rocket motor thrusters, with thrusts ranging from milli-pounds force to several tens of pounds of thrust, and are capable of sustained thrust profiles or may be pulsed at over 30Hz. Specifically, the paper focuses on a cube-sat design utilizing a number of such small electric propellant thrusters in an optimized form factor that maximizes historically underutilized structure volume with the use of additive manufacturing. The specific power demand and power supply bus integration are discussed, as are results from propellant space environment and hazard class testing. Overall, the packaged design promises to deliver significant impulse and enhanced capabilities for a range of mission profiles and can be integrated directly with new and existing cube-sat payloads. Owing to its inherent simplicity and reduced parts-count, the cost target for this new type of controllable propulsion is nearly an order of magnitude more affordable than current comparable controllable propulsion offerings.

BACKGROUND

Since 2010 Raytheon has been investigating a new class of solid propellants that are electrically activated. These propellants, based on ionic salts, are basically inert until an electric current is passed through them at which point they exhibit an electro-chemical reaction. Raytheon first became aware of these propellants as a result of an interaction with a small business partner, Digital Solid State Propulsion, LLC (DSSP). These propellants are collectively referred to as “electric propellants,” or simply ePropellants.¹

For more than 10 years, DSSP had demonstrated the safety and controllability of ePropellants in many applications.^{2,3,4,5} The DSSP formulations are based on a hydroxylammonium nitrate (HAN) oxidizer and have been subjected to safety and insensitive munitions (IM) testing. Subsequent work with these propellants continues to demonstrate the high potential for safe, controllable propulsion.

In order to capitalize on the characteristics of ePropellants Raytheon, working both independently and with DSSP, investigated existing formulations and pursued ePropellants that could meet a wider range of

requirements. Several formulations were tested and found to have the potential for a combination of performance and stability. Raytheon has since patented a unique class of electric propellant and has conducted extensive testing. The propellant, named *Phoenix*TM ePropellant, does not use HAN but alternatively uses a perchlorate based oxidizer.

One difference between the HAN based propellants and the Phoenix ePropellant is that based on testing in a pressurized environment the Raytheon electric propellant formulation will not sustain combustion without an electrical input at operationally relevant pressures. The HAN formulations will self-sustain burning above threshold pressures of approximately 200 psi. PhoenixTM ePropellant can be turned off/restarted at high motor pressures. This characteristic widens the potential applications for which these safe, solid propellants may be utilized and promises the potential of true on/off operation at all pressure levels.

On-going IR&D efforts have continued to demonstrate the viability of this new technology for thrusters, gas generators, igniters, and other commercial applications. The thruster is especially promising for small satellite

applications. Initial testing demonstrated repeatable operation in a thrust class and form factor consistent with medium to high ΔV maneuvers in small CubeSats; see Figure 1.

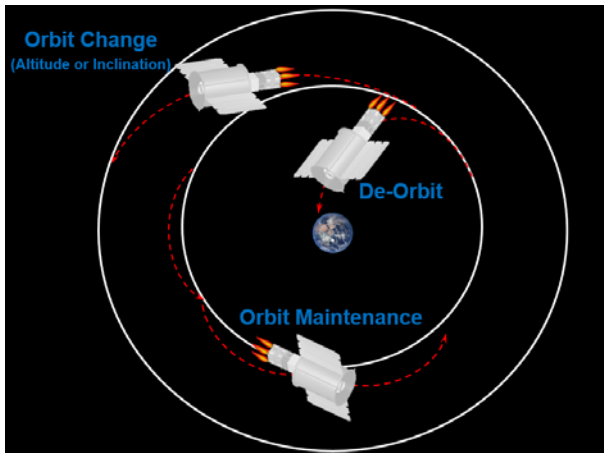


Figure 1—High delta-V maneuvers

Raytheon has continued to partner with DSSP to define the strategies to continue the development of this promising technology. The highest potential near-term applications continue to be small thrusters. Raytheon considers small business and potentially, university, partnerships to be especially attractive to participate in a larger development effort due to the ease with which the critical technologies could be accommodated in an industrial park or university lab setting enabling the development work to be spread among enough entities to allow rapid advancement to a product. The inherent safety of this material is a true enabler in development as well as end use.

TECHNOLOGY CHARACTERISTICS

On-off and throttleable solid chemical propulsion

The propellant may be throttled as well as turned on and off with only electrical current. This is truly a breakthrough for solid propellants and allows for much more efficient propellant use versus conventional solid propulsion. The propellant may be throttled during a single pulse as it reacts more energetically with higher current densities, and being that the propellant is self-extinguishing, it may be turned on and off by the application and removal of a threshold current density. Raytheon has demonstrated 255 pulses on a single grain of Phoenix ePropellant.

Simple design

ePropellant Thruster designs are very simple. In its simplest form, ePropellant thrusters need only have two

electrodes with propellant in between and a power supply to function. This leads to a very simple and cost-effective system. Figure 2 shows one thruster design that has been successfully tested. This particular thruster housing and nozzle were additively manufactured. Cost targets are an order of magnitude below small hydrazine thrusters due in large part to this inherent simplicity.

The ePropellant grains are likewise simple to manufacture. Mix/cast/cure are accomplished in a matter of a few days and recent developments with 3D printing have shown positive results for just-in-time additive manufacture of the ePropellant, housing and possibly the electrodes.



Figure 2—Phoenix ePropellant thruster

Safe

The propellant appears to be nearly inert. ePropellant is activated by a relatively high threshold current density, whereby it becomes energetic comparable to conventional solid propellants. This makes the material very safe to handle and insensitive to outside stimuli including direct flames and electro-static discharge. Explosives Bureau D.O.T. testing completed in 2015 validated that the propellant was insensitive to the following stimuli: Thermal soak (75°C oven 48 hours), Small-scale burn (fire), detonation/shock (blasting caps), friction sensitivity, and impact sensitivity. Additional tests have included pulse barriers in between conventional Ammonium Perchlorate Composite Propellant (APCP) grains, direct torch testing, electrostatic discharge, and a number of other thermal/pressure environments, where in all cases the propellant has successfully self-extinguished. Preliminary hazard classification is 1.4 for Phoenix ePropellant. This point is especially important as conventional solid rocket motors have a hazard classification of 1.3 (in some cases 1.1), which translate to significantly different storage and handling requirements, and thus cost.

3D printable

The propellant may be cast or 3D printed. Raytheon has developed the capability to 3D print ePropellant

with a modified fused deposition modeling printer. See Figure 3. This allows for new and innovative propellant configurations with conventional or additive manufacturing techniques. ePropellant could even be “printed” into the structure of the small satellite enabling even more propellant capacity.

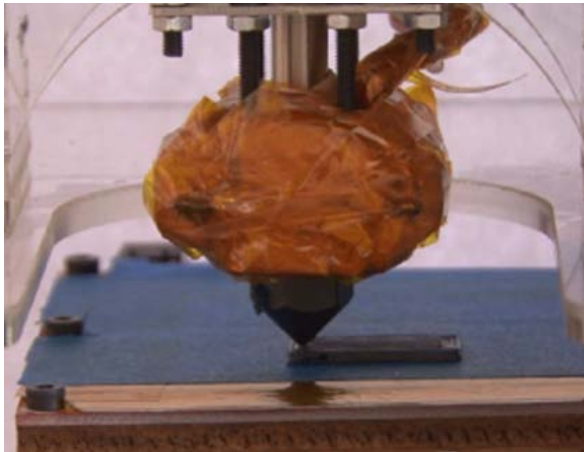


Figure 3—3D printing of Phoenix ePropellant

CubeSat compatible power requirements

Thrusters may be powered by typical CubeSat power supplies. The thrusters demonstrated to date may be powered with a relatively low wattage power supply that charges a small capacitor bank. This allows controlled pulses that may be fired as soon as the capacitor bank is charged. Current estimates show two thrusters may be fired roughly every 8 seconds with 8V and 20W feeding the system. Alternately, a high output battery may be employed for maneuvers requiring more rapid impulse generation.

Environmentally friendly

The precursors and products of combustion are not especially hazardous. Unlike other solid rocket propellants the Raytheon Phoenix ePropellant does not require elaborate environmental controls for testing. Once combustion takes place, the resulting products are not generally considered hazardous once the initial plume has cleared. Furthermore, the material may be produced with general lab safety measures (gloves, goggles and respirators) since the constituent components and mixed material are stable and virtually inert.

RECENT ADVANCEMENTS

1U compatible thruster demonstrated

In August of 2015, Raytheon demonstrated a proof-of-concept 3D printed 1U compatible thruster with 255 individual pulses on a single ePropellant grain

controlled only with electrical power. See Figure 2. Pulses were estimated at levels appropriate for CubeSat medium/high delta V maneuvers and were consistently repeatable. Several of these thrusters were tested. A second generation thruster was designed and tested to more accurately measure performance. See Figure 4. This thruster is undergoing testing throughout 2016. Preliminary results demonstrate choked flow with a large reduction in the power required to sustain combustion compared to initiation as measured in continuous operation.



Figure 4—1U compatible thruster demonstrated

1U compatible power supply test bed

Integral to the function of any ePropellant thruster is the power supply and conditioning system. Raytheon has developed a 1U compatible power supply and conditioning test bed. This test bed is designed to function with typical CubeSat available power at 8V input, 20W of power, and interface with standard CubeSat bus. Figure 5 shows the test bed Circuit Card Assemblies (CCAs) inserted into a 1U 4x ePropellant thruster chassis with a high output thermal battery model (gray). Note that a high output thermal battery would allow for very rapid pulsing of the thrusters.

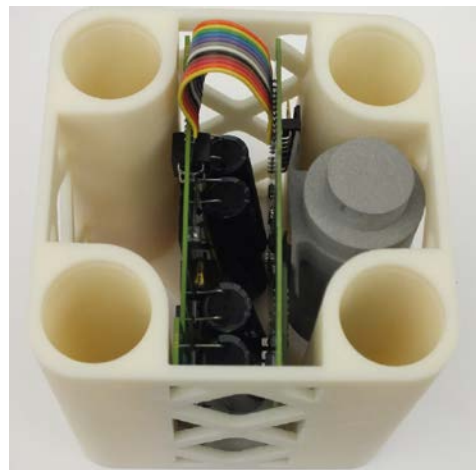


Figure 5—1U power supply test bed boards in 3D printed 4 thruster configuration

The design allows for two thrusters to fire simultaneously to ostensibly minimize torque in the case of a multiple thruster configuration as pictured in Figure 5.

This power supply and conditioning test bed CCA was designed to be compatible with CubeSat bus protocols as well as allow for significant flexibility for different thruster and mission requirements. Once a final design is determined, the board design can be consolidated and packaging optimized for space and power efficiency. Raytheon has just begun testing this power supply

CONCLUSION

The small satellite propulsion application is tailor made for ePropellants as it provides a simple and safe high-impulse solution. The form factors, thrust levels and total impulse needed for small satellites have been demonstrated by both Raytheon and DSSP. Both classes of ePropellant are safe to handle, minimize parts count, and are easy to manufacture which translates to an affordable thruster solution.

An integrated product development team consisting of industry, small businesses, universities and government labs is desirable to more rapidly develop, manufacture, and transition this technology to commercial and military products. We believe that with breakthroughs of the past year, the technology is at the cusp of that transition.

References

1. Sawka, W. and McPherson, M., "Electrical Solid Propellants: A Safe, Micro to Macro Propulsion Technology," AIAA Paper 2013-4168, presented at 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Jose, CA, July 14-17, 2013.
2. Sawka, W.N., Katakian, A. and Grix, C., "Solid State Digital Cluster Thrusters for Small Satellites, Using High Performance Electrically Controlled Extinguishable Solid Propellants," Paper SSC05-XI-3, 19th Annual AIAA/USU Small Satellite Conference, 2005.
3. Grix, C., Katakian, A., and Sawka, W.N., "Throttled Propulsion Using an Electrically Controlled Extinguishable, Solid Propellant Dual Stage Motor, 24th JANNAF Rocket Nozzle Technology Subcommittee Meeting, San Diego, CA, November 2005.
4. Katakian, A., Grix, C. and Sawka, W.N. Electrically Controlled Extinguishable Solid Propellants: A Safe, Broadly Scalable Propulsion Technology, 53rd JANNAF Propulsion Meeting, Monterey, CA, December 2005.

5. Sawka, W.N., "Pulse Performance and Power Requirements for Electrically Controlled Solid Propellant," 55th JANNAF Propulsion Meeting, Las Vegas, NV, April 2009.