AIAA Propulsion and Energy Forum
August 24-28, 2020, VIRTUAL EVENT
AIAA Propulsion and Energy 2020 Forum

10.2514/6.2020-3930

Multi-pulse Solid Rocket Motor Technology

Frederick B. Koehler[1] and Mark J. Meisner[2] and Jeff L. Vollin[3]
Raytheon Missiles and Defense, Tucson, Arizona, 85716 USA

In pursuit of optimal thrust profiles for solid rocket motors, Raytheon has developed an electrically activated solid propellant technology that is applicable to both multi-pulse motors and continuously variable thrusters. This new propellant called Phoenix™ ePropellant is inert until a threshold electrical power is applied whereby it combusts. Safety testing has been performed which preclude Phoenix™ ePropellant from Class I per the U.S. Department of Transportation and it does not require special explosives handling. Multi-pulse motors have been demonstrated that will allow three or more pulses on a single motor with only a thin layer of Phoenix™ ePropellant in between pulses to both stop one grain combustion and ignite the next. Small thrusters have been demonstrated that may be pulsed hundreds of times and each pulse may be throttled depending upon the amount of electrical power supplied.

I. Introduction

The overarching advantage of multi-pulse rocket motors is the capability for direct command ignition of the subsequent solid propellant grain segments (i.e., pulses) on-demand. This allows for near optimal energy management of the propellant burn[1]. The key advantage to this approach is that all of the pulse segments are contained in a single rocket motor case—as opposed to staged rocket motors. This saves weight and potentially cost and can provide extended range. Ideally, each pulse can have a different thrust level, burn time, and specific impulse. This is achieved by tailoring the specific formulation of the propellant, segment size, burn rate, and grain design[2]. A key advantage is the variation of the inter-pulse delay. Short inter-pulse delays have the rocket motor behave like a single pulse motor, whereas, longer delays can allow for a more tailored energy management[3] as required by the mission profile such as longer or more evasive missions[4]. One variation of this theme is the continuously variable thrust motor which can be arbitrarily turned on and off without pre-set propellant segments using only electrical current to throttle and ignite or extinguish the solid propellant. This has been demonstrated in small form factors suitable for applications such as small satellites[5]. Figure 1 shows one of Raytheon's continuously variable small Phoenix ePropellant Thrusters.

Figure 1, Small Electrically Activated Solid Propellant Thruster[5]

II. Background

Raytheon has been researching electrically activated solid propellants since 2010 when it began working with formulations based on a hydroxylammonium nitrate (HAN) oxidizer which was capable on-off combustion with electrical current[6]. The HAN formulation, however proved too limited for some of Raytheon's applications as it would sustain combustion at higher chamber pressures. Raytheon therefore began to investigate alternate formulations without HAN and arrived at the current formulation based on perchlorate oxidizers as described in the Raytheon

[1] Principal Systems Engineer, Systems Design and Integration Department.
[2] Engineering Fellow, Technology Development Office, Member AIAA.
[3] Principal Engineering Fellow, Technology Development Office.

Patents[7,8]. The current formulation maintains the on-off properties of the HAN formulation, however, it does not sustain combustion at higher pressures typical of conventional solid rocket motors. This expansion of the self-extinguishing pressure threshold is greatly advantageous to many applications particularly when used as a pulse separation barrier-igniter for a conventional solid rocket motor as described in the Raytheon patent[9]. Another manifestation of this new propellant is enhanced safety. The material will not sustain combustion after the electrical stimulus is removed. This new formulation was subjected to a slate of safety testing by Explosives Bureau and was subsequently excluded from the Class I explosive category per the U.S. Department of Transportation. The handling of the material is therefore greatly simplified and allows it to be used in otherwise prohibited applications such as ride-shares on orbital launch vehicles where more traditional satellite propellants like hydrazine and other hypergolic propellants would be prohibited.

As research has progressed, two applications have surfaced as leading candidates for this technology: Pulse separation barrier-igniters and small thrusters. Small thruster concepts have been demonstrated in relevant size and thrust for pico-, nano-, and micro-satellites with as many as 255 pulses demonstrated on a single grain of propellant controlled with electricity only. The pulse barrier-igniter technology has been demonstrated to show the practicality of three or more pulses on a single rocket motor.

III. Technology Applications

A. Phoenix ePropellant Small Thrusters

There are a wide variety of uses for small thrusters comprising both exo- and endo-atmospheric platforms. For endo-atmospheric applications, the Raytheon patented[10] thruster in its current form would be limited to attitude control systems. Conversely, the Raytheon Phoenix ePropellant thruster could enable large delta V maneuvers, such as orbit transfers, for pico-, nano-, and micro-satellites. Solid rocket motors provide high thrust but are traditionally single use devices and therefore provide limited utility for space systems. Liquid systems, however, with hypergolic propellants such as hydrazine are controllable and have high thrust, but are often not allowed on ride-share platforms due to hazard exposure. Electric propulsion to include hall-effect, pulsed plasma, and other ion-type thrusters, generally provide high Isp, but low thrust and are therefore used primarily for low delta V maneuvers. Phoenix ePropellant thrusters could provide another option for exo-atmospheric propulsion with controllable high thrust impulse bits with a ride-share compatible chemistry[7]. Figure 2 shows Phoenix ePropellant thrusters in the satellite propulsion trade space.

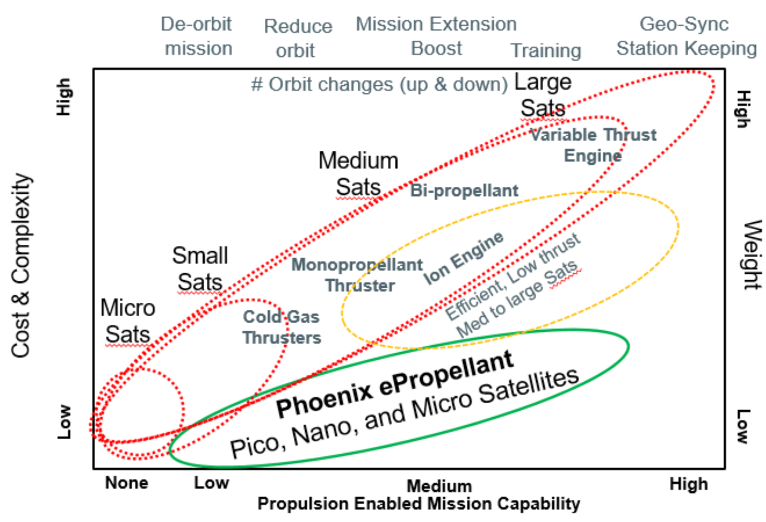

Figure 2, Raytheon ePropellant small thrusters could fit an under-served niche in small satellite propulsion[5]

This document does not contain technology or technical data controlled under either the U.S. International Traffic in Arms Regulations or the U.S. Export Administration Regulations.

One patented[11] version of the Phoenix ePropellant Thruster is shown in Figure 3. This thruster consists of a thruster body (14) and nozzle (24). It has segmented Phoenix ePropellant grains (34) sealed against the vacuum of space with a moisture barrier (36). There is a pushing mechanism (31) that keeps the propellant grains against the electrodes (16) so they may be ignited with electrical input.

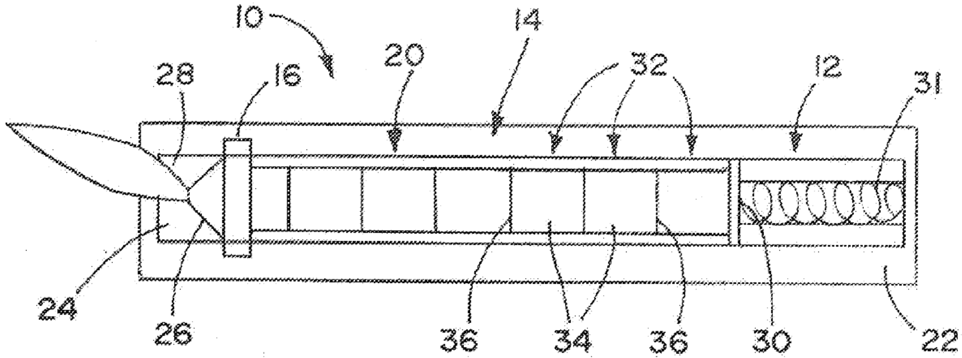

Figure 3 Segmented Phoenix ePropellant Thruster[11]

Raytheon has demonstrated 255 pulses on one propellant grain built from several segments in a small thruster shown in Figure 4.

Figure 4, Phoenix ePropellant Small Thruster[5]

B. Phoenix ePropellant Barrier-Igniters for Multi-Pulse Solid Rocket Motors

Multi-pulse rocket motors have been used for decades as a means to tailor the thrust profile of solid rocket motors. They have generally been limited to two or three pulses due to the high overhead in terms of complexity, cost, and impact to propellant mass fraction (the mass of propellant as a proportion of the mass of the rocket motor). Multi-pulse motors have a barrier, either hard or soft, in between pulse grains. They also have to have an igniter system which allows ignition of one grain while being isolated from any subsequent grains. Phoenix™ ePropellant Barrier-Igniter technology simplifies this system by having the barrier also function as the igniter as described in the Raytheon patent[9]. The concept is illustrated in Figure 5 which shows a notional two-pulse rocket with Phoenix ePropellant Barrier-Igniters used to ignite both pulse 1 (24) and pulse 2 (26) of the rocket. From left to right, the battery (60) sends power to the barrier-igniter electrodes. The anode (35) and cathode (34) of each igniter sandwich a layer of Phoenix ePropellant (33) which ignites when signaled. This is the simplest form of the technology with a flat wafer of Phoenix ePropellant on an end-burning propellant grain. More complex grain forms are possible to change the performance of each pulse.

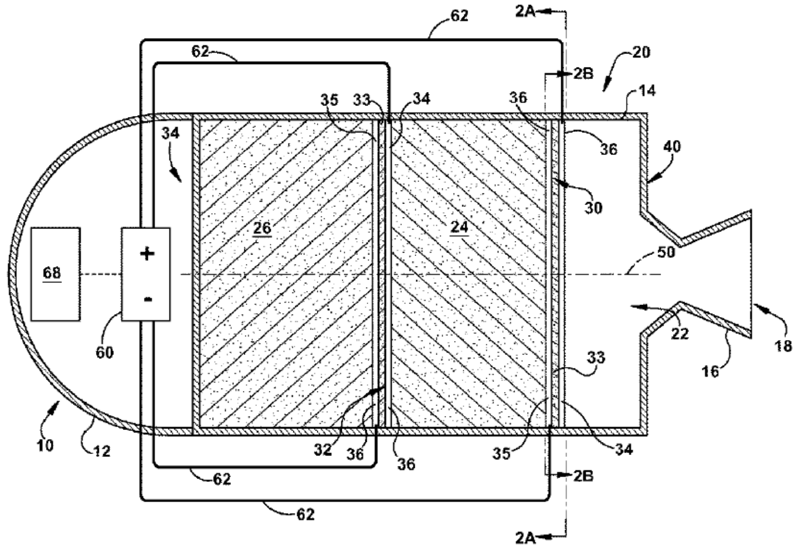

Figure 5 Phoenix ePropellant Barrier-Igniter Concept[9]

Figure 6 shows one option for a contoured grain using the Phoenix ePropellant Barrier-Igniter. In this case, pulse 1 (84) would begin burning from a center placed Phoenix ePropellant Barrier-Igniter (82) and burn left in a roughly conic fashion into the conic annular pulse 2 grain (88). Pulse 2 will then ignite when pulse 2 barrier-igniter (86) is commanded. The contoured grain will burn in a conic form which yields a larger surface burn area and higher thrust than a flat end-burning grain.

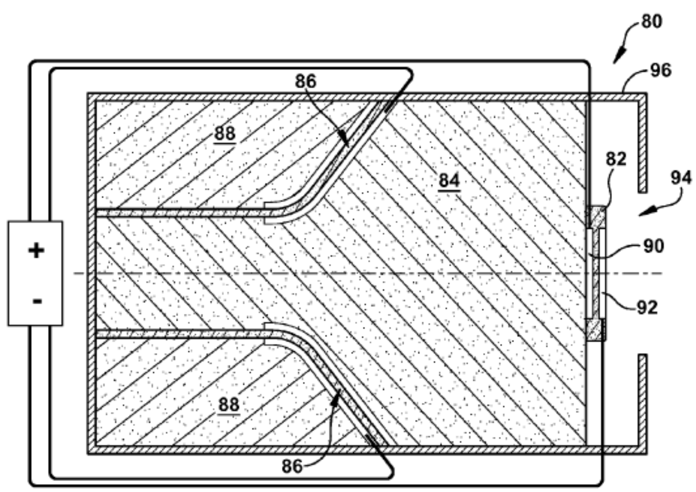

Figure 6 Conic Annular Phoenix™ ePropellant Barrier-Igniter[9]

The electrode configurations are important and must be designed deliberately. Figure 7 shows a Phoenix ePropellant barrier-igniter electrode configuration. Figure 7a. shows the cathode (34) wires and Figure 7 shows the anode (35) wires. The electrode will determine the character of the ignition event, in this case finer vs. coarser mesh of electrodes.

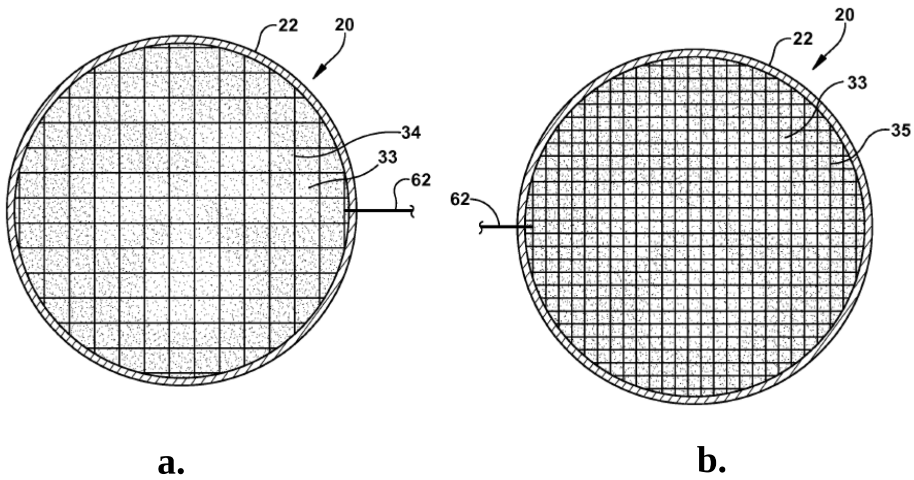

Figure 7 Phoenix ePropellant Barrier-Igniter Electrode Configuration[9]

This technology has been demonstrated with one, two, and three pulses, though the concept could extend to additional pulses. Figure 8 shows one of the multi-pulse solid rocket motor experiments. The inset is an open-air test of the Phoenix ePropellant Barrier-Igniter ignition event.

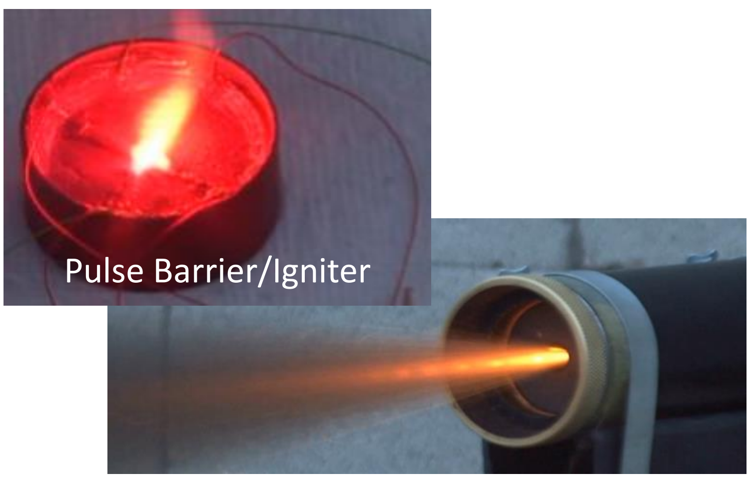

Figure 8 Phoenix™ ePropellant Barrier-Igniter Motor Demonstration

C. Other Applications

The current paper focuses on the two most mature applications of Phoenix ePropellant, which are not exhaustive. Raytheon has a patent[12] on using this technology for tunable automobile air-bags, for instance, whereby the inflation rate and amount of air-bag inflation can be tuned to match the severity of the collision. Applications where a controlled gas generation is required and adequate electrical power is available would be candidates for this technology.

IV. Conclusion

Phoenix ePropellant technology has the potential to approach the tailored thrust profiles of liquid rocket motors with the safety and long-term storage benefits of solid propellants. As the immediate applications of small thrusters and pulse barrier-igniters continue to show promise and are developed further, the understanding of the physics of how the material can be leveraged will improve and expand leading to more optimized and alternative applications.

References

[1] Phillips, C.A, “Energy Management for a Multiple Pulse Missile,” AIAA Paper 88-0334, January 1988.

[2] “Pulsed rocket motor,” Wikipedia, https://en.wikipedia.org/wiki/Pulsed_rocket_motor.

[3] Jensen, G.E, and Netzer D.W., “Tactical Missile Propulsion,” AIAA Progress in Astronautics and Aeronautics, Volume 170, (1996).

[4] Naumann, K. and Stadler, L., “Double-Pulse Solid Rocket Motor Technology - Applications and Technical Solutions,” 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 25 July 2010 - 28 July 2010, Nashville, TN, Published Online 15 November 2012.

[5] Koehler, Frederick B., et.al., 2017 “Electric Propellant Solid Rocket Motor Thruster Results Enabling Small Satellites,” Proceedings of the AIAA/USU Conference on Small Satellites, Session 2, Advanced Technologies 1, SSC17-11-02.

[6] 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.

[7] Villarreal, James K., Loehr, Richard D., Raytheon Company, Waltham, MA, U.S. Patent for “Electrically Activated Solid Propellants,” Patent No.: US 8,950,329 B2, filed 24 December 2012.

[8] Loehr, Richard D., Villarreal, James K., Raytheon Company, Waltham, MA, U.S. Patent for “Electrically Activated Solid Propellant with Elevated Self-Sustaining Threshold Pressures,” Patent No.: US 10,220,809 B2, filed 20 July 2016.

[9] Villarreal, James K., Langhenry, Mark T., Summers, Matt H., Macinnis, Daniel V., Raytheon Company, Waltham, MA, U.S. Patent for “Electrically Activated Pulse Initiators and Ignition,” Patent No.: US 10,107,601 B2, filed 6 October 2015.

[10] Koehler, Frederick B., et.al., Raytheon Company, Waltham, MA, U.S. Patent Application for “Satellite with Integrated Thrusters,” Patent Application No.: US 2020/0024003 A1, filed 4 February 2019.

[11] Koehler, Frederick B., Lyman, Ward D., et.al., Raytheon Company, Waltham, MA, U.S. Patent Application for “Thruster with Segmented Propellant,” Patent Application No.: US 2017/0284339 A1, filed 5 April 2016.

[12] Villarreal, James K., et.al., Raytheon Company, Waltham, MA, U.S. Patent for “Electrically Controlled Variable Force Deployment Airbag and Inflation,” Patent No.: W) 2015/183596 A3 filed 15 May 2015.