Electric Solid Propellants

Steven Sharp

AERO 540 – Elements of Rocket Propulsion

CAL POLY

Solid Propellants

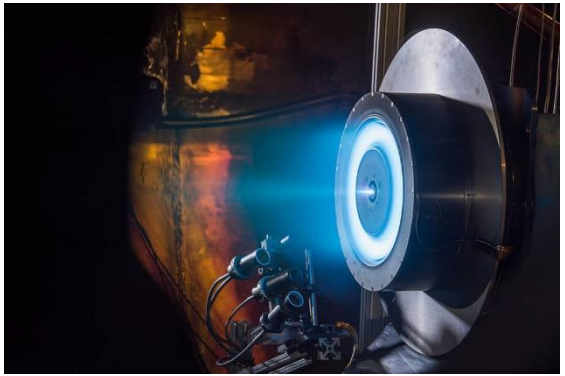
- Low I_{sp}, high thrust
- Throttle passively controlled by grain configuration
- Can usually only be stopped once per mission
  - Explosive charges
  - Extinguishing gases
- Usually extremely reactive
  - High performance propellants especially explosive

https://www.nasa.gov/exploration/features/dm3.html

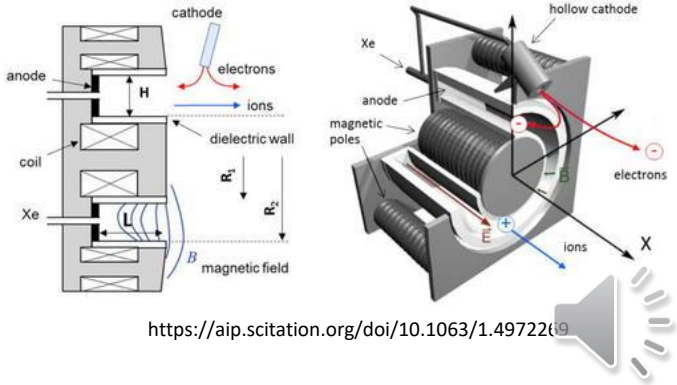
Cape Canaveral Space Force Museum [YouTube]

Electric Propulsion

- High I_{sp}, low thrust
- Throttle actively controlled by field strength and feed current
- Can be stopped and restarted quickly and easily
- Requires complex and expensive components
- Strong fields could potentially fry the spacecraft's circuits (DART)



https://www.nasa.gov/image-feature/nasa-glenns-hall-thruster



https://aip.scitation.org/doi/10.1063/1.4972269

Electric Solid Propellants

What if we combine solid and electric propulsion?

Best of both worlds?

Or ineffective compromise?

History

- 1990s – AN-based contact-safe vehicle airbag propellant
- 1999 – Air Force funds development of ASPEN[1]
  - Digital Solid State Propulsion (DSSP) emerges as the primary developer of ESP
  - AN base with additives to increase conductivity
- 2005 – DSSP announces HIPEP[1]
  - Hydroxyl ammonium nitrate (HAN) + polyvinyl alcohol (PVA)
- 2011 – W. Sakwa of DSSP patents thruster stack design[2]
- 2015 – DSSP proposes multi-pulse motor to NASA[3]
- 2023 – DSSP producing ESP for pyrotechnics and VFX[4]

[1] Sakwa et al, "Solid State Digital Propulsion 'Cluster Thrusters' For Small Satellites, Using High Performance Electrically Controlled Extinguishable Solid Propellants", 19th Annual AIAA/USU Conference on Small Satellites, 2005
[2] U.S. Patent 7,958,823 B2 [3] NASA Proposal 14-2 S3.02-8755
[4] "Pyrotechnic Products and Systems", Digital Solid State Propulsion (https://dssptech.com/pyrotechnics)

HIPEP Recipe

- How to cook your own HIPEP? [5][6][7] (Don't try this at home)

HAN

- Neutralize hydroxylammonium sulfate with an alkali hydroxide
- Distill the resulting aqueous hydroxylamine solution at <50 mmHg and <65° C
- Add the hydroxylamine solution to 20-70% wt. nitric acid solution in a reactor at -50–30 °C and vigorously agitate
- Further mix in a reactor and adjust the proportion of nitric acid until the pH of the solution is between 1.0 and 1.5

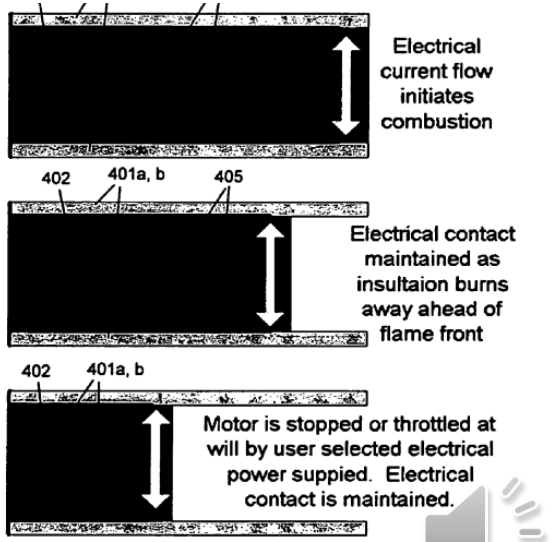
HIPEP

- Add 20% powdered PVA and 5% powdered AN to the resulting hydroxylammonium nitrate solution
- Reduce pressure in a vacuum chamber until bubbling stops
- Pour and mold the resulting gel, bake until hardened

[5] U.S. Patent 5,266,290
[6] Glascock et al, "Impulse Measurements of Electric Solid Propellant in an Electrothermal Ablation-Fed Pulsed Plasma Thruster", AIAA Propulsion and Energy 2019 Forum
[7] Interview with Wayne Sakwa and Trisha Buescher at DSSP by Integza (https://www.youtube.com/watch?v=eHRyv7ARb5M)

Aerospace Applications

- Pulsed Plasma Thrusters
  - Can replace PTFE (Teflon) for ablative propulsion
  - Not as efficient due to high conductivity limiting arc generation[1]
- ESP thrusters
  - HIPEP between two electrodes with ablative insulation to maintain contact
  - Propellant burns only when constant current is produced between the electrodes
  - Main energy source from thermal expansion of gas, not ionization

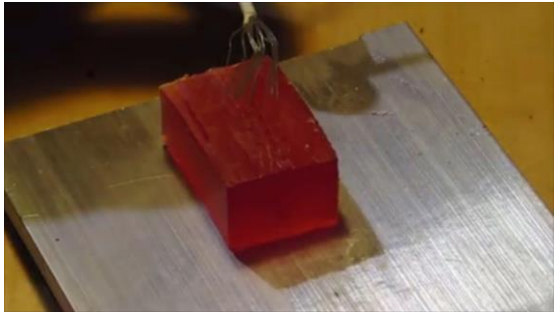


U.S. Patent 7,958,823 B2

[1] Sakwa, W. N., A. Katzakian and C. Grix, "Solid State Digital Propulsion 'Cluster Thrusters' For Small Satellites, Using High Performance Electrically Controlled Extinguishable Solid Propellants", 19th Annual AIAA/USU Conference on Small Satellites, 2005

Advantages

- Advantages
  - No moving parts
  - No strong electric or magnetic fields
  - High energy density characteristic of solids
  - I_{sp} higher than most solids (240-270 s)[8]
  - Controlled ignition upon application of electrical current



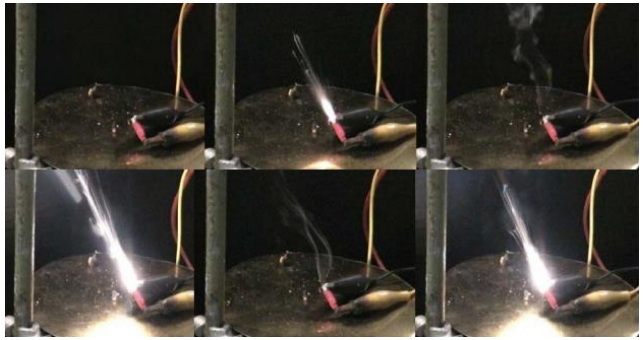
https://www.youtube.com/@DSSPropulsion

[8] Multi-Pulse Motor (MPM) Designed for Use with Electric Solid Propellants, Tech Briefs (https://www.techbriefs.com/component/content/article/tb/pub/briefs/aerospace/24104)

Advantages

- Throttleable, extinguishable and restartable with simple current variance

https://www.youtube.com/@DSSPropulsion



W. Sakwa at DSSP[1]

- Non-toxic and unreactive
  - Extreme impact, spark, and flame resistance
  - Safe ground handling
  - Can handle extreme G force

https://www.youtube.com/@DSSPropulsion

Disadvantages

- I_{sp} higher than solids but much lower than EP
- Combustion becomes uncontrollable at large scales like launch vehicle boosters[7]
- PTFE is already a widely available and inert propellant for PPT applications
- HIPEP is not widely available
  - DSSP is the only commercial producer
- Low interest from space agencies and private companies
  - More investment in improving existing solids and EP systems

[7] Interview with Wayne Sakwa and Trisha Buescher at DSSP by Integza (https://www.youtube.com/watch?v=eHRyv7ARb5M)

Non-Aerospace Applications

- Concert pyrotechnics
- Film VFX
  - Muzzle flashes
  - Electrical arcing
  - Small explosions
- Theme parks
- Explosive simulators for military training

Potential Use Cases

- Cheap, simple, throttleable thruster for low-budget missions
  - CubeSats
  - Constellations
  - Trajectory correction maneuvers for sub-orbital missiles
- Bimodal thrusters for SSTO planes
  - DSSP developing GEM electric liquid propellant
    - Catalyzed for thermal expansion in atmosphere
    - Ionized in vacuum
- Refuelable satellites, space stations, Moon & Mars bases
  - HIPEP is an excellent choice when storage safety is critical

Conclusion

- A throttleable, restartable, safe storage solid propellant sounds amazing… but is it?
  - The performance is great for a solid propellant but terrible for EP
  - It can’t be used for launch vehicle boosters, only small sats
  - Electric propulsion is already easily throttleable
- There aren’t many reasons to use ESP over solids
- The main advantages are the high thrust and simplicity of the system when compared to EP
  - The most probable use case would be for CubeSats and constellations where budget is thin and sats are expendable
- Overall, ESPs are cool but have not yet proven themselves to be more useful than either solids or EP

References

[1] Sakwa, W. N., A. Katzakian and C. Grix, “Solid State Digital Propulsion ‘Cluster Thrusters’ For Small Satellites, Using High Performance Electrically Controlled Extinguishable Solid Propellants”, 19th Annual AIAA/USU Conference on Small Satellites, 2005

[2] U.S. Patent 7,958,823 B2

[3] NASA Proposal 14-2 S3.02-8755

[4] “Pyrotechnic Products and Systems”, Digital Solid State Propulsion (https://dssptech.com/pyrotechnics)

[5] U.S. Patent 5,266,290

[6] Glascock, M. S., J. Rovey and K. Polzin, “Impulse Measurements of Electric Solid Propellant in an Electrothermal Ablation-Fed Pulsed Plasma Thruster”, AIAA Propulsion and Energy 2019 Forum

[7] Interview with Wayne Sakwa and Trisha Buescher at DSSP by Integza (https://www.youtube.com/watch?v=eHRyv7ARb5M)

[8] Multi-Pulse Motor (MPM) Designed for Use with Electric Solid Propellants, Tech Briefs (https://www.techbriefs.com/component/content/article/tb/pub/briefs/aerospace/24104)

[9] Glascock, Matthew, “Characterization of a Green Electric Solid Propellant for Electric Propulsion”, Ph.D Aerospace Engineering, Missouri Institute of Science and Technology, 2019

[10] Thirumalvalawan, I. Patel, R. Aggarwal, “A Study on Electrically Controlled Solid Propellants”, International Journal of Engineering Sciences & Research Technology, Oct. 2015