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ARTICLE

GREEN PROPULSION TECHNOLOGIES FOR SUSTAINABLE SPACE MISSIONS: A MISSION-ORIENTED REVIEW

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Abstract: While hydrazine is the reference propellant for many spacecraft reaction-control and orbit-maintenance systems today, its toxicity, handling burden and regulatory pressure have driven a search for safer alternatives. In line with this, the review in this paper gives a mission-oriented comparison of green spacecraft propulsion options. The reviewed literature is published from 2000 to May 2026, which are identified using major databases, agency reports, conference papers and also selected flight-heritage sources. The discussion covers ADN/LMP-103S, HAN/ASCENT, high-test peroxide, nitrous-oxide systems, green hybrid and bipropellant concepts and electric propulsion using iodine or krypton. The comparison uses specific impulse, density impulse, storage behavior, catalyst or ignition needs, thermal and material limits, toxicity, maturity, cost implications and mission suitability. On the whole, it is found that ADN and HAN monopropellants appear to be the most practical near-term chemical replacements for many hydrazine applications. Meanwhile, HTP and nitrous-oxide systems are useful where the safety and simpler operations matter more than peak performance. Furthermore, iodine and krypton electric propulsion are not direct hydrazine substitutes for impulsive maneuvers but they can reduce the reliance on xenon in low-thrust missions. The main remaining barriers are catalyst durability, high-temperature materials, storage qualification, repeatable starts and system-level flight verification.

Keywords: ADN monopropellant, green propulsion, HAN monopropellant, hydrazine replacement, space propulsion

1. Introduction

In general, spacecraft propulsion is chosen by balancing thrust, impulse, propellant volume, power, storage life, safety, cost and mission assurance. At the moment, hydrazine monopropellant thrusters have remained attractive because they are compact, restartable and supported by decades of component and flight heritage. Typical small hydrazine systems deliver about 200 to 235 s of specific impulse, which is adequate for many reaction-control, station-keeping, momentum-dumping and disposal tasks [1]-[3]. Nevertheless, there is an ongoing problem with regard to the handling of hydrazine. Hydrazine is acutely toxic and therefore might require SCAPE-class procedures during spacecraft processing. These rules protect personnel but they add cost, schedule constraints and launch-site complexity. Subsequently, a replacement for hydrazine has been researched. The potential replacement has to be more than just less toxic; it must also work with tanks, valves, heaters, catalysts, seals, filters, control electronics and mission duty cycles [4]-[7].

This review study treats green propulsion as a practical engineering choice for replacing hydrazine. Among others, this includes ADN and HAN monopropellants, high-test peroxide, nitrous-oxide-based systems, selected green hybrid or bipropellant concepts and alternative-propellant electric propulsion such as iodine or krypton. It should be noted that these technologies do not solve the same problem. In short, ADN and HAN are closest to hydrazine replacement for compact chemical thrust, HTP and nitrous oxide offer safer handling for selected missions and iodine or krypton electric propulsion mainly supports long-duration low-thrust operation [8]-[11]. All things considered, the primary contribution of this review study is a compact mission-oriented framework that links performance, density impulse, handling risk, storage, catalyst or ignition needs, maturity, economic handling effects and also spacecraft class.

2. Methodology for Literature Review

Overall, the review uses Scopus, Web of Science, ScienceDirect, NASA NTRS, ESA and CORDIS material, AIAA and Small Satellite Conference papers, and also selected agency or manufacturer sources where mission status or flight heritage is reported. The main search period is from 2000 to May 2026. In addition, older sources are retained only when they provide baseline theory or historically important propulsion data. For this study, the search terms that are used include green monopropellant, hydrazine replacement, ADN, LMP-103S, HAN, AF-M315E, ASCENT, high-test peroxide, green hybrid rocket, nitrous oxide propulsion, iodine electric propulsion, krypton Hall thruster and small satellite propulsion. Sources are included when they contain any spacecraft-relevant performance, storage, handling, catalyst, material or mission data. On the other hand, aviation-fuel papers, broad sustainability articles without propulsion data, duplicate conference summaries and unverifiable claims are excluded [12]-[14]. This search strategy is summarized in Table 1.

Table 1: Condensed literature-search strategy

Source Group	Role in the Review	Typical Use
Journal databases	Peer-reviewed studies on green propellants, catalysts, materials, and electric propulsion	Technical discussion and performance ranges
NASA, ESA, CORDIS	Mission demonstrations, regulatory context, and spacecraft technology reports	Flight status, handling motivation, and system-level data
AIAA and SmallSat proceedings	Recent system demonstrations and small-spacecraft propulsion results	Updated maturity and mission examples
Manufacturer/agency pages	Used only when peer-reviewed sources did not give flight heritage or operational status	Supplementary heritage and handling information

3. Hydrazine Baseline and Comparison Metrics

Hydrazine decomposes over a catalyst bed and produces hot gases for nozzle expansion. Its real advantage is system maturity: tanks, valves, thrusters, catalyst beds, handling procedures and mission-design practices are well established. For a green replacement, matching the ideal specific impulse is not enough. The system must also store safely for years, start repeatedly, survive thermal cycling and remain compatible with spacecraft materials [1, 3]. The comparison in this study therefore uses several metrics: specific impulse, propellant density, normalized density impulse, storage behavior, catalyst or ignition requirement, toxicity, flight heritage, technology readiness, cost and handling implications, and mission fit. For volume-limited spacecraft, density impulse is useful since it links propellant density to delivered impulse. In simplified form, this is given by Equation 1 where ρ_p and $I_{sp,p}$ are the density and specific impulse of the candidate propellant whereas ρ_{hyd} and $I_{sp,hyd}$ represent the corresponding values for hydrazine. Although this metric supports preliminary screening, final propellant selection still requires mission-specific thruster performance data.

$$D_{norm} = \frac{\rho_p I_{sp,p}}{\rho_{hyd} I_{sp,hyd}} \tag{1}$$

In the meantime, Figure 1 depicts the considered green propulsion options in this study, which are grouped by mission function.

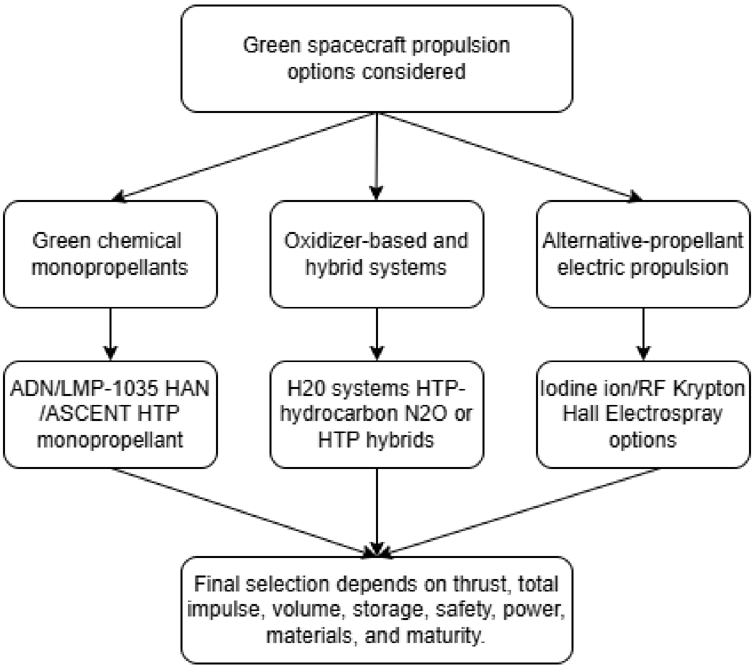

Figure 1: Green propulsion options as grouped by mission function

4. Main Green Propulsion Options

ADN-based propellants, especially LMP-103S, are among the most mature hydrazine alternatives. Their higher density improves volumetric impulse and flight experience from PRISMA and later small-satellite missions has shown that they are no longer only laboratory candidates. Recent ECAPS material reports broad HPGP 1-N thruster heritage and useful storage evidence for pre-loaded spacecraft [15]-[17]. The main caution is the hotter catalyst-bed environment and the need for robust catalyst, heater, and material compatibility [18]. On the other hand, HAN/ASCENT, formerly AF-M315E, offers one of the strongest density-impulse gains among chemical green propellants. NASA GPIM gives important in-space evidence that the propellant, tank, feed system, valves, heaters and thrusters could work as an integrated subsystem [19]-[21]. The challenge is that HAN decomposition is thermally and catalytically complex. Catalyst structure, bed length, startup behavior, pressure and heat management strongly affect performance and life [22]-[26].

Meanwhile, high-test peroxide (HTP) can be used as monopropellant or an oxidizer in bipropellant and hybrid systems. It decomposes mainly into steam and oxygen, which makes it attractive from the toxicity viewpoint. Its monopropellant I_{sp} is lower than ADN or HAN but its density, versatility and simpler exhaust products keep it relevant for missions where safety and also moderate performance are more important than maximum impulse [27]-[31]. However, it is noted that concentrated peroxide still requires careful cleanliness, stabilizer control and material selection. Moreover, nitrous oxide (N2O) is useful since it is self-pressurizing and less hazardous than hydrazine in normal handling. It can simplify the small feed systems and can work as an oxidizer in hybrid or bipropellant designs [32]-[34]. However, it is not risk-free: decomposition, temperature-dependent pressure and also ignition reliability must be controlled. Green hybrid systems using HTP or N2O with solid fuels such as paraffin, polyethylene or ABS can support larger impulse classes but they still need to solve regression-rate control, mixture-ratio shift and restart qualification [35]-[38].

Last but not least, iodine and krypton address a different sustainability problem: dependence on xenon. Iodine can be stored as a solid and has already been demonstrated in orbit while krypton offers a lower-cost noble-gas option for several Hall thruster missions [39]-[45]. These systems are attractive for station keeping, drag compensation, orbit raising and deorbiting when long burn time is acceptable. They should not be described as direct hydrazine replacements for fast impulsive maneuvers [46]-[48].

5. Comparative Assessment

Table 2 summarizes the main technologies in a compact form. The values are representative ranges; actual performance depends on thruster size, chamber pressure, nozzle expansion, catalyst condition, thermal state, pulse mode, feed losses and qualification margin.

Table 2: Compact comparison of green propulsion options

Technology	Typical Performance	Best Use	Main Limitation	Sources
Hydrazine	200-235 s; mature liquid monopropellant	Benchmark RCS and station keeping	Severe toxicity and ground-handling burden	[1]-[7]
ADN / LMP-103S	235-252 s class; higher density than hydrazine	Small / medium spacecraft needing chemical thrust	Catalyst preheat, bed life, compatibility	[8, 15, 16, 17, 18]
HAN / ASCENT	240-255 s class; very strong density impulse	Volume-limited spacecraft and high-density chemical systems	High temperature and catalyst / material life	[19]-[26]
HTP	160-185 s as monopropellant; versatile oxidizer	Low-toxicity moderate-performance systems	Contamination and material sensitivity	[27]-[31]
N2O systems	Architecture dependent; self-pressurizing	Simple small systems and hybrid/bipropellant concepts	Thermal-pressure sensitivity and decomposition risk	[32]-[34]
Hybrid / bipropellant	About 250-330 s depending on design	Larger impulse and safer separate storage	Regression, mixture-ratio, ignition repeatability	[35]-[38]
Iodine EP	Low-thrust EP; compact solid storage	CubeSat and smallsat low-thrust missions	mN-class thrust and iodine compatibility	[42]-[44]
Krypton EP	Hall-class EP; lower cost than xenon	Constellations, station keeping, long burns	Lower efficiency than xenon and power demand	[39]-[45]

Furthermore, the screening-level comparison of density impulse and maturity for selected chemical options is depicted in Figure 2 while the hybrid and alternative-propellant electric propulsion envelope is presented in Table 3.

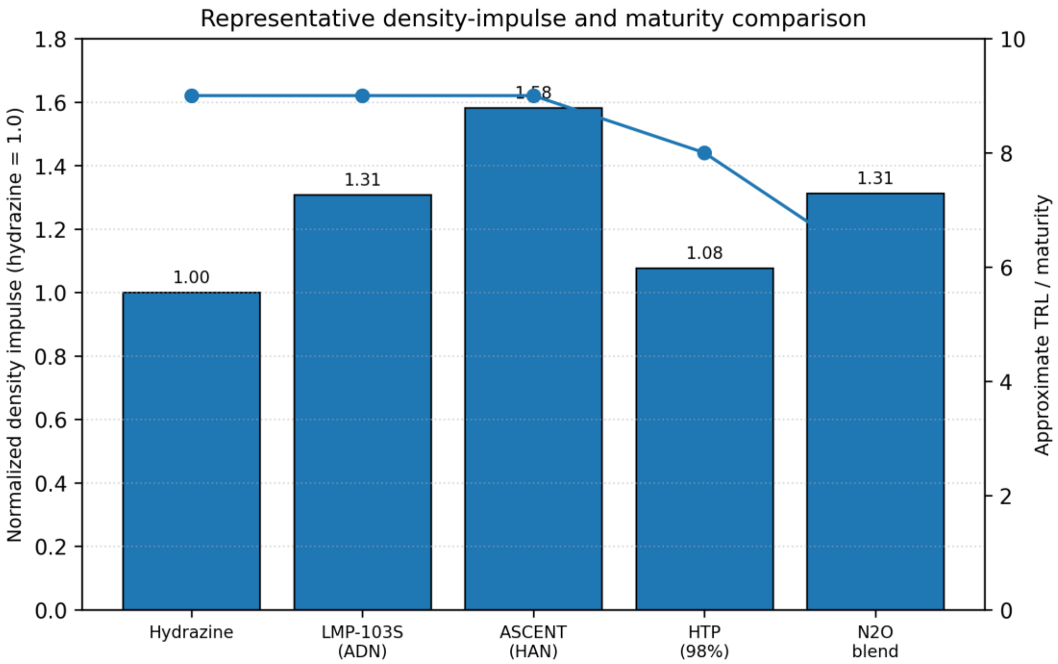

Figure 2: Screening-level comparison of density impulse and maturity for selected chemical options

Table 3. Hybrid and alternative-propellant electric propulsion envelope

System	Representative I_{sp}	Practical Role	Main Caution
HTP or N2O hybrid	About 250-330 s; N to kN class	Safe larger-impulse manoeuvres and demonstrations	Restart and regression-rate control
HTP / hydrocarbon bipropellant	About 250-320 s; N to kN class	Higher-performance green chemical option	More feed and ignition complexity
Iodine RF EP	About 550-650 s in compact low-power class; sub-mN to mN	CubeSat orbit maintenance and drag compensation	Very low thrust and material compatibility
Iodine ion / Hall concepts	About 1000-3000+ s; mN to tens of mN	Long-duration orbit raising or station keeping	Less mature than xenon EP
Krypton Hall thruster	About 1000-2500 s; mN to hundreds of mN	Constellation economics and station keeping	Lower efficiency than xenon for similar hardware

On the whole, ADN and HAN are the strongest near-term chemical candidates. HAN has the best density-impulse argument while ADN has strong operational heritage. HTP and nitrous oxide are useful for safer handling and selected architectures. Hybrid and bipropellant systems extend the impulse range but add integration complexity. Iodine and krypton electric propulsion are valuable complements, not universal hydrazine substitutes.

6. Mission Suitability and Recent Progress

The best option changes with the mission needs. A CubeSat may value packaging and low handling burden. In contrast, a responsive spacecraft may need pre-loading and simple ground operations while a GEO spacecraft may prioritize qualification history. Moreover, a deep-space mission may accept low thrust if electric propulsion reduces propellant mass. All in all, the mission suitability map is tabulated in Table 4.

Table 4: Mission suitability map

Mission Need	Likely Option	Reason	Caution / Evidence
CubeSat or smallsat manoeuvres	ADN, HAN, compact HTP, iodine EP	Compact packaging and reduced handling burden	Startup, heater power, and thermal control matter [3, 46, 47]
Earth-observation orbit maintenance	ADN or HAN	Chemical thrust with improved processing safety	Mission-specific qualification still required [16, 20]
Responsive or pre-loaded spacecraft	ADN/HPGP, selected HTP	Lower toxicity can simplify ground operations	Long storage compatibility remains important [16]-[17]
Lunar or cislunar small spacecraft	HAN or iodine/krypton EP	Choose chemical thrust for fast manoeuvres or EP for long low-thrust arcs	Thermal-vacuum storage and duty cycle are critical [13, 14, 42]
Large impulse or upper-stage concepts	HTP hybrid or green bipropellant	Separate storage and higher total impulse	Less mature for routine spacecraft RCS [35]-[36]
Long-duration station keeping	Iodine or krypton EP	High effective I_{sp} and lower xenon dependence	Requires power and long burn time [39]-[45]

The recent trend is encouraging. GPIM demonstrates ASCENT at subsystem level; ADN-based HPGP has accumulated small-satellite heritage; iodine EP has been operated in orbit; and the current HTP/HAN research is improving catalysts, decomposition control and thruster design [20, 22, 23, 30, 42]. These results highlight that the field is moving from propellant chemistry toward full propulsion-system qualification.

7. Economic, SDG and Qualification Issues

Advanced manufacturing and advanced combustion concepts, including additive manufacturing and detonation-based systems, may support future green propulsion hardware development, but they are included here only as enabling technologies since their sustainability value depends on qualification, repeatability and also mission integration [49]-[53]. The economic case should be stated carefully. Cost depends on mission class, launch site, propellant quantity, safety rules and contract terms. Published AF-M315E material has reported average conventional-propellant loading cost of about USD 135,000 for NASA missions while AF-M315E loading was expected to require only a small fraction of that cost because range operations and protective handling requirements were simpler [54]. This value should be interpreted as a ground-processing and loading-cost comparison, not as purchase price of the propellant itself. NASA and AFRL also note that both ASCENT and LMP-103S can reduce SCAPE-type handling needs compared to hydrazine [20, 54, 55]. The sustainability link is thus practical rather than absolute: green spacecraft propulsion mainly supports safer industrial practice, responsible chemical use, cleaner ground processing and more sustainable space infrastructure, which are most closely related to SDG 9, SDG 12 and SDG 13 [56]-[58]. The identified main benefits and remaining gaps are listed in Table 5.

Table 5: Main benefits and remaining gaps

Area	Short Finding	Relevant Technologies
Handling and cost	Lower toxicity can reduce SCAPE-class operations, hazardous-waste burden, and launch-site delays, but savings are site-specific	ADN, HAN, HTP; SDG 9 and 12 [54]-[57]
Safety	Green propellants reduce some risks but do not remove all hazards; peroxide contamination and N2O decomposition still need careful control	HTP, N2O, hybrids [27]-[34]
Catalyst durability	Repeated pulses can damage catalysts, change pressure drop, or cause start-transient problems	ADN, HAN, HTP [18, 22, 23]
Materials and storage	Hotter monopropellants and reactive fluids need better chamber, seal, tank, and feed-system qualification	ADN, HAN, HTP, iodine [16, 17, 24, 44]
Mission validation	Hot-fire tests alone are not enough; thermal-vacuum, vibration, duty-cycle, and integrated flight tests are needed	All systems [12, 13, 48]
Sustainability link	The SDG value is mainly safer infrastructure, responsible chemical handling, and support for sustainable space operations, not direct launch decarbonization	SDG 9, 12, and 13 [56]-[58]
Manufacturing and advanced concepts	Additive manufacturing and advanced combustion may help, but qualification and repeatability remain essential	All systems, RDEs [49]-[53]

8. Conclusion

Green spacecraft propulsion is now a practical mission-dependent technology area rather than only an environmental aspiration. Both ADN/LMP-103S and HAN/ASCENT are the two strongest near-term chemical hydrazine alternatives because they combine useful thrust, higher density impulse, lower handling hazard and growing flight evidence. On the other hand, HTP and nitrous oxide are attractive where safety, simplicity or hybrid/bipropellant architecture matters, although they require strict material and hazard control. Meanwhile, iodine and krypton electric propulsion provide a complementary route for long-duration low-thrust missions and can reduce dependence on xenon. On the whole, no option is universally best. The sound approach is to select propulsion by mission need: thrust level, burn time, volume, power, storage life, ground processing, maturity and qualification risk. The remaining work is mainly engineering: longer catalyst life, better high-temperature materials, safe storage, repeatable starts and system-level testing under the representative mission conditions. The strongest non-performance benefits are the reduced toxic-handling burden, possible ground-processing saving and better alignment with responsible chemical use and sustainable space operations. It should be noted that this paper is a review and screening study, not an experimental validation campaign. The performance values are the representative literature ranges and should not be used as final design numbers. A real mission requires thruster-specific data, nozzle and feed losses, duty cycle, heater power, thermal-vacuum qualification, spacecraft volume and power constraints. Manufacturer sources are used primarily for flight heritage or operational status whereas peer-reviewed and agency sources are prioritized for technical claims.

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References

[1] G. P. Sutton, O. Biblarz and J. H. Morehart, Rocket Propulsion Elements, John Wiley & Sons, 2026.
[2] R. W. Humble, G. N. Henry and W. J. Larson, Space Propulsion Analysis and Design, McGraw-Hill, 1995.
[3] Small Spacecraft Technology State of the Art: In-Space Propulsion [Online]. Retrieved from https://www.nasa.gov/smallsat-institute/sst-soa/in-space_propulsion/#4.1
[4] Substance Infocard: Hydrazine [Online]. Retrieved from https://echa.europa.eu/substance-information/-/substanceinfo/100.005.560
[5] Hydrazine: NIOSH Pocket Guide to Chemical Hazards [Online]. Retrieved from https://www.cdc.gov/niosh/npg/npgd0329.html
[6] Green Advanced Space Propulsion (GRASP): Final Report Summary [Online]. Retrieved from https://cordis.europa.eu/project/id/218819/reporting
[7] Is Water the Best New Propellant for Future Space Missions? [Online]. Retrieved from https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Is_water_the_best_new_propellant_for_future_space_missions
[8] H. K. Ciezki, 'Short Overview on the Development of Advanced Green Monopropellants for Satellite Propulsion Applications – Status Summer 2025', Aerospace, vol. 12, no. 12, 1093, 2025.
[9] D. Freudenmann and H. K. Ciezki, 'ADN and HAN-based Monopropellants – A Minireview on Compatibility and Chemical Stability in Aqueous Media', Propellants, Explosives, Pyrotechnics, vol. 44, no. 9, pp. 1084-1089, 2019.
[10] I. Remissa, H. Jabri, Y. Hairch, K. Toshtay, M. Atamanov, S. Azat and R. Amrousse, 'Propulsion Systems, Propellants, Green Propulsion Subsystems and Their Applications: A Review', Eurasian Chemico-Technological Journal, vol. 25, no. 1, pp. 3-19, 2023.
[11] A. Hai, D. Darfilal, F. AlHammadi, S. S. Syed, H. Alhashmi, A. Nabi and S. S. M. Swei. (2026). Propelling Sustainability: Green and Alternative Fuels for Space Missions [Online]. Retrieved from 10.5772/intechopen.1013180.
[12] B. Ridgeway. (2015). Green Propellant Infusion Mission (GPIM) Overview [Online]. Retrieved from www.nasa.gov/missions/tech-demonstration/green-propellant-infusion-mission-gpim-overview/
[13] Lunar Flashlight Mission and Propulsion Information [Online]. Retrieved from https://www.jpl.nasa.gov/
[14] CAPSTONE [Online]. Retrieved from https://www.nasa.gov/mission/capstone/
[15] K. Anflo, B. Crowe and R. Persson, 'Flight Demonstration of New Thruster and Green Propellant Technology on the PRISMA Satellite', Acta Astronautica, vol. 65, no. 9-10, pp. 1238-1249, 2009.
[16] W. Dingertz, P. Thormählen and O. Christofi, 'ECAPS High-Performance Green Propulsion-Enabling Tactically Responsive Space Missions', Proceedings of the Small Satellite Conference, Logan, USA, August 2024.
[17] LMP-103S and High Performance Green Propulsion (HPGP) Technology [Online]. Retrieved from https://ecaps.se/
[18] 3D Catalysts for Improved Hydrazine-free Propellants [Online]. Retrieved from https://cordis.europa.eu/article/id/230144-3d-catalysts-for-improved-hydrazinefree-propellants
[19] C. H. McLean, 'Green Propellant Infusion Mission: Program Construct, Technology Development and Mission Results', Proceedings of the AIAA Propulsion and Energy Forum, Online, August 2020.
[20] B. Ridgeway. (2020). NASA's Green Propellant Infusion Mission Nears Completion [Online]. Retrieved from https://www.nasa.gov/missions/tech-demonstration/nasas-green-propellant-infusion-mission-nears-completion/

[21] 88th Air Base Wing Public Affairs. (2019). Green Propellant Infusion Mission to Test AFRL-Developed Green Propellant [Online]. Retrieved from www.afrl.af.mil/News/Article/2339580 /green-propellant-infusion-mission-to-test-afrl-developed-green-propellant/

[22] W. S. Chai, K. H. Cheah, M.-H. Wu, K. S. Koh, D. Sun and H. Meng, 'A Review on Hydroxylammonium Nitrate (HAN) Decomposition Techniques for Propulsion Application', Acta Astronautica, vol. 196, pp. 194-214, 2022.

[23] Y. Kasbi, I. Remissa, K. Toshtay, A. Mabrouk, A. Bachar, S. Azat, A. E. S. Nosseir, A. Tiwari, E. M. Sabbar and R. Amrousse, 'H_2O_2 and HAN Green Monopropellants – A State-of-the-Art Review on Their Recent Development, Corresponding Synthesized Catalysts and Their Possible Use as Thrusters', Catalysts, vol. 15, no. 2, 183, 2025.

[24] A. Wada, H. Watanabe and H. Takegahara, 'Combustion Characteristics of a Hydroxylammonium-nitrate-based Monopropellant Thruster with Discharge Plasma System', Journal of Propulsion and Power, vol. 34, no. 4, pp. 1052-1060, 2018.

[25] A. Fukuchi, S. Nagase, H. Maruizumi and M. Ayabe, 'HAN/HN-based Monopropellant Thrusters', IHI Engineering Review, vol. 43, no. 1, pp. 22-28, 2010.

[26] D. Sun, G. Zhang, T. Yao and L. Guan, 'Influence of Catalyst Bed Structure on Performance of HAN-based Monopropellant Engine', Acta Aeronautica et Astronautica Sinica, vol. 45, no. 16, 129818, 2024.

[27] M. Ventura and P. Mullens, 'The Use of Hydrogen Peroxide for Propulsion and Power', Proceedings of 35th Joint Propulsion Conference and Exhibit, Los Angeles, USA, June 1999.

[28] D. D. Davis, L. A. Dee, B. Greene, S. D. Hornung, M. B. McClure and K. A. Rathgeber, 'Fire, Explosion, Compatibility and Safety Hazards of Hydrogen Peroxide', NASA/TM-2004-213151, 2005.

[29] W. Kopacz, A. Okninski, A. Kasztankiewicz, P. Nowakowski, G. Rarata and P. Maksimowski, 'Hydrogen Peroxide – A Promising Oxidizer for Rocket Propulsion and Its Application in Solid Rocket Propellants', FirePhysChem, vol. 2, no. 1, pp. 56-66, 2022.

[30] U. Kokal, M. Baysal, N. B. Emerce, Y. Yıldız, A. Karabeyoğlu and İ. Özkol, 'Evaluation and Performance Optimization of a Hydrogen Peroxide-based Green Monopropellant Thruster for Steady-state Operations', Aerospace, vol. 12, no. 2, 136, 2025.

[31] L. Mezyk, J. Kindracki, K. Wacko, P. Wozniak, M. Kostecki, M. Petrus, P. Surmacz and F. V. Bel, 'Initial Investigation of Catalyst Pack for 98%+ Hydrogen Peroxide Satellite Monopropellant Thruster', Acta Astronautica, vol. 225, pp. 913-927, 2024.

[32] S. A. Whitmore, C. Merkley and S. D. Eilers, 'Operational Characteristics of Nitrous Oxide Based Monopropellant and Bipropellant Options for Small Spacecraft', Proceedings of the AIAA/USU Conference on Small Satellites, Logan, USA, 2013.

[33] Industry Update: Prevalence of Nitrous-Based In-Space Propellants [Online]. Retrieved from https://www.dawnaerospace.com/latest-news/prevalence-of-nitrous-based-in-space-propellants

[34] G. Mungas, M. Vozoff and B. Rishikof, 'NOFBX: A New Non-Toxic 'Green' Propulsion Technology with High Performance and Low Cost', Proceedings of International Astronautical Congress, Naples, Italy, October 2012.

[35] A. Okninski, P. Surmacz, B. Bartkowiak, T. Mayer, K. Sobczak, M. Pakosz, D. Kaniewski, J. Matyszewski, G. Rarata and P. Wolanski, 'Development of Green Storable Hybrid Rocket Propulsion Technology using 98% Hydrogen Peroxide as Oxidizer', Aerospace, vol. 8, no. 9, 234, 2021.

[36] P. Surmacz, 'Green Rocket Propulsion Research and Development at the Institute of Aviation: Problems and Perspectives', Journal of KONES Powertrain and Transport, vol. 23, no. 1, pp. 337-344, 2016.

[37] B. Cantwell, A. Karabeyoglu and D. Altman, 'Recent Advances in Hybrid Propulsion', International Journal of Energetic Materials and Chemical Propulsion, vol. 9, no. 4, 2010.

[38] M. A. Karabeyoglu, D. Altman and B. J. Cantwell, 'Combustion of Liquefying Hybrid Propellants: Part 1, General Theory', Journal of Propulsion and Power, vol. 18, no. 3, pp. 610-620, 2002.
[39] D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters, John Wiley & Sons, 2008.
[40] S. Mazouffre, 'Electric Propulsion for Satellites and Spacecraft: Established Technologies and Novel Approaches', Plasma Sources Science and Technology, vol. 25, no. 3, 033002, 2016.
[41] G. F. Benavides, H. Kamhawi, T. M. Liu, L. R. Pinero, T. R. Verhey, C. R. Rhodes, J. Yim, J. Mackey, T. G. Gray, N. I. Butler-Craig, J. L. Myers and A. G. Birchenough, 'Development of a High-Propellant Throughput Small Spacecraft Electric Propulsion System to Enable Lower Cost NASA Science Missions', Proceedings of the AIAA Propulsion and Energy Forum, Indianapolis, USA, August 2019.
[42] D. Rafalskyi, J. M. Martínez, L. Habl, E. Z. Rossi, P. Proynov, A. Boré, T. Baret, A. Poyet, T. Lafleur, S. Dudin and A. Aanesland, 'In-orbit Demonstration of an Iodine Electric Propulsion System', Nature, vol. 599, no. 7885, pp. 411-415, 2021.
[43] N. Bellomo, M. Magarotto, M. Manente, F. Trezzolani, R. Mantellato, L. Cappellini, D. Paulon, A. Selmo, D. Scalzi, M. Minute and M. Duzzi, 'Design and In-Orbit Demonstration of REGULUS, an Iodine Electric Propulsion System', CEAS Space Journal, vol. 14, no. 1, pp.79-90, 2022.
[44] Sublimable Propellant Source for Iodine-fed Ion Propulsion System [Online]. Retrieved from https://technology.nasa.gov/patent/mfs-tops-85
[45] I. Levchenko, S. Xu, G. Teel, D. Mariotti, M. L. R. Walker and M. Keidar, 'Recent Progress and Perspectives of Space Electric Propulsion Systems Based On Smart Nanomaterials', Nature Communications, vol. 9, no. 1, 879, 2018.
[46] K. Lemmer, 'Propulsion for Cubesats', Acta Astronautica, vol. 134, pp. 231-243, 2017.
[47] D. Krejci and P. Lozano, 'Space Propulsion Technology for Small Spacecraft', Proceedings of the IEEE, vol. 106, no. 3, pp. 362-378, 2018.
[48] L. Blondel-Canepari, 'A Holistic Framework for Mission-Specific Propulsion System Selection', PhD Thesis, Università di Pisa, 2025.
[49] A. Montanaro, D. Piazzullo, D. Tortorici, A. Ingenito and L. Allocca, 'Green Rocket Propulsion: Overview of Nitrous Oxide Applications with Emphasis on Hybrid Systems', Fuel, vol. 406, 137036, 2026.
[50] P. R. Gradl. (2022). Metal Additive Manufacturing for Rocket Propulsion Applications [Online]. Retrieved from https://ntrs.nasa.gov/api/citations/20220014027/downloads/Metal%20AM%20for%20Rockets%20and%20HEX_23_Sept_2022_Rev1.pdf?attachment=true
[51] I. Gibson, D. Rosen, B. Stucker, M. Khorasani, D. Rosen, B. Stucker and M. Khorasani, Additive Manufacturing Technologies, Springer, 2021.
[52] K. Kailasanath, 'Review of Propulsion Applications of Detonation Waves', AIAA Journal, vol. 38, no. 9, pp. 1698-1708, 2000.
[53] S. D. Heister, J. Smallwood, A. Harroun, K. Dille, A. Martinez and N. Ballintyn, 'Rotating Detonation Combustion for Advanced Liquid Propellant Space Engines', Aerospace, vol. 9, no. 10, 581, 2022.
[54] R. Masse, M. Allen, R. Spores and E. A. Driscoll, 'AF-M315E Propulsion System Advances and Improvements', Proceedings of 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, USA, July 2016.
[55] B. Ridgeway. (2020). NASA's Green Propellant Infusion Mission Nears Completion [Online]. Retrieved from https://www.nasa.gov/missions/tech-demonstration/nasas-green-propellant-infusion-mission-nears-completion/

[56] Goal 9: Build Resilient Infrastructure, Promote Sustainable Industrialization and Foster Innovation [Online]. Retrieved from https://www.un.org/sustainabledevelopment/infrastructure-industrialization/
[57] Goal 12: Ensure Sustainable Consumption and Production Patterns [Online]. Retrieved from https://www.un.org/sustainabledevelopment/sustainable-consumption-production/
[58] Goal 13: Take Urgent Action to Combat Climate Change and Its Impacts [Online]. Retrieved from https://www.un.org/sustainabledevelopment/climate-change/