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Propellant Technologies: Far-Reaching Benefits for Aeronautical and Space-Vehicle Propulsion

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Rocket propellant and propulsion technology improvements can be used to reduce the development time and operational costs of new space-vehicle programs. Advanced propellant technologies can make the space vehicles safer, more operable, and better performing. Five technology areas are described: monopropellants, alternative hydrocarbons, gelled hydrogen, metalized gelled propellants, and high-energy density materials. The benefits of these propellants for future vehicles are outlined using mission study results and the technologies are briefly discussed.

Introduction

SPACE exploration and utilization require vehicles that are operable, safe, and reliable. Technologies for improving rocket performance are also desirable. As space missions become more ambitious, the needs for reducing cost and increasing the capability of rocket systems will increase. Propellant technologies have the power to make space flight more affordable and deliver higher performance.

Throughout the world a new set of space-related activities is being formulated. Many nations are taking advantage of the powerful view of Earth from orbit and beyond. New space activities in the U.S. are planned that include small expendable boosters, larger reusable launch vehicles (RLVs), high-speed aircraft, and new small spacecraft for many commercial and civilian space operations.[1] These new space-planning activities have identified the need for new lower-cost ways of gaining access to space, and much effort is being expended on this difficult issue. The cost of space access is particularly vexing because many people and much infrastructure is usually associated with large orbital aerospace and rocket vehicles. One option to reduce space access costs is propellant technologies. Advances made over the last 60 years in propellants have shown that propellants can be made safer, less costly, and/or more energetic.[2–4] Investing in propellant technologies can provide benefits across the board to all major international programs and NASA enterprises.[1,5–7]

With the recent advent of RLVs,[7–12] the investigation of combined cycle and combination propulsion, [13–15] and the development of small boosters for low-cost spacecraft,[5,6,16,17] the interest in advanced propellants has risen. With RLVs, there is a need for propellants that improve the vehicle mass fraction, as the goal of single-stage-to-orbit (SSTO) makes unceasing demands on the performance of lightweight materials, cryogenic systems, and, of course, rocket propulsion. Combined and combination propulsion, using both airbreathing and rocket propulsion, are another set of options for SSTO and two-stage-to-orbit (TSTO) vehicles. These vehicles will also stress the limits of many technologies, and high density, high-energy hydrocarbons, and hydrogen will be needed. Advanced cooling techniques with endothermic fuels are also attractive for many applications. Small boosters are also in vogue. The use of small boosters for space access has become more attractive, particularly for entrepreneurs attempting to use space for profitable gain, and universities who wish to use space flight, satellite construction, and satellite operation as learning tools.

High-speed aircraft, with fleet foot, perhaps approaching orbital velocities, are also in the plans for commercial gain, national power projection, observation, and space access.[7,8,13–15] These aircraft require cooling technologies for their airframes as well as for their internal systems, passengers, and payloads. Typically, the fuel is used as a heat absorber, but hypersonic flight requires cooling capacities that exceed that of traditional fuels. Endothermic fuels have the capacity to thermally break up and split into components. This breakup of the fuel absorbs heat and increases the fuel-cooling capacity.

Many studies have shown the powerful leverage gained with high-performance upper stages.[18–20] High specific-impulse propellants with high density can reduce the size of launch vehicles, thereby permitting the performance of the same mission with a smaller launch vehicle and reducing the cost of space access. Improving these upper stages has led to the use of O_2/H_2 propellants, but the low density of H_2 has hampered the ability of upper stages to be packaged in a small volume. The search for higher propellant and stage density has led to several directions. Additives to H_2 or the use of alternative hydrocarbons may allow the upper stage to deliver the same payload performance while occupying a smaller volume, and reduce the overall launch vehicle mass and cost.

Spacecraft-propulsion technology improvements are critically important in reducing space vehicle costs.[21–24] Reducing the mass and size of the spacecraft, as well as its upper stages, can reduce the size of the launch vehicle needed. As the propulsion system is often the largest and most massive component of a spacecraft, there is a powerful leverage to be gained

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with higher-density, higher-performance propellants. Size reductions can often allow the integration of functions that further reduce overall vehicle costs, such as the combining of apogee propulsion for orbit circularization, and the use of the same propellants and engines for on-orbit maneuvering and orbit maintenance.

The future also beckons with new propellants born of the computer and the propellant designer.[25,26] Many dream of harnessing the most powerful chemical bonds between individual atoms of hydrogen, boron, carbon, and aluminum. The atoms, once created, are arrested within a cryogenic solid, and released as they enter the rocket engine. Though these propellants are currently difficult to fabricate in large quantities, there is hope that the power of molecular manipulation from microtechnology, and ultimately nanotechnology, will make these new, and in some cases not yet known, propellants a shining reality.

Five major areas of propellant technologies will be discussed in this paper. The influence of these technologies on vehicle design, some of the current research interests, and the status of the technologies will be addressed. A short overview of the importance of density and specific impulse is also provided to illustrate the main issues in the development of propellant technologies.

Liquid rocket propellants are often the largest volume onboard a rocket vehicle. Their large volume must be contained by very large, bulky, heavy tanks that keep the liquids at the right pressure and temperature until they are used in a rocket engine. An increase in the density, or mass per volume, can reduce the mass of the tanks, structure, and other parts of the rocket that are dependent upon the volume of the propellants. Higher-density propellants are therefore an excellent way to improve the performance of rocket vehicles because they will reduce the mass of the tanks and the associated components. Reducing the mass of the rocket will also lead to reducing the weight of fuel needed to move the rocket, and so there is a powerful cascade effect that occurs when reducing the mass of rockets and the amount of fuel.

Reducing the weight of a rocket is also made possible by using a higher-energy fuel because less fuel is needed. This energy is related to the exhaust velocity or specific impulse of the rocket engine, essentially a miles-per-gallon analogy for rockets. The higher the energy of the fuel, the higher the specific impulse. Adding energy to the fuel by changing its chemistry, gelling the fuel, or gelling and adding particles of metal or other higher energy compounds, can increase the specific impulse.

Several ways of increasing the density of the propellants have been used in the past. One way of increasing propellant density is to create a special chemical mixture with high density, such as a high-density salt that is soluble in water. Another way is to use very high-density chemical fuels existing in nature: Aluminum, boron, or other metals. A third way is to add small metal particles, or frozen liquid particles, and suspend them in the fuel or oxidizer. A gelling agent is used to thicken the fuel and allow the suspension of the solid particles. The gelling agent may be frozen liquid particles, solid particles, or long-chained liquid polymers. Gelling the fuel, without adding metal particles, can also increase the density and change the energy of the fuel. The gelling agent can add energy and increase the density by itself, but the energy and density increases are much larger if metal additives are also used.

With these ideas of increased density and specific impulse in mind, the five technologies are described and their applications and effect on future missions are discussed.

Technologies

Five major areas have been identified for fruitful research. The five areas are monopropellants, alternative hydrocarbons, gelled hydrogen, metallized gelled propellants, and high-energy density propellants. During the development of the NASA Advanced Space Transportation Plan, these technologies were identified as the most likely to have high leverage for new NASA vehicles for each of the enterprises.[1] This work is continuing under other programs, recently realigned under the three pillars of NASA: Global Civil Aviation, Revolutionary Technology Leaps, and Access to Space.

Monopropellants

Current spacecraft and satellite users and manufacturers are looking for more environmentally benign and safer propellants.[27–32] Environmental, safety, and cost concerns with hydrazine (N_2H_4) and its derivatives have led to the development of monopropellants with a high water content and high energy additives. Monopropellants, based on hydroxyl ammonium nitrate (HAN), have a density that is up to 1400 kg/m^3, this is about 40% higher than hydrazine.[32] The potential specific impulse of these monopropellants is in the range of 210–270 s. Although the first versions of the fuels may have comparable or lower specific impulses than hydrazine, the cost associated with launch processing and the ground-crew's safety are significantly reduced with the new monopropellants. Safer propellants can reduce costs by eliminating the need for the self-contained atmospheric protective ensemble (SCAPE) suits[33] that are needed for toxic propellants. Also, extensive and prohibitive propellant safety precautions and the isolation of the space vehicle from parallel activities during propellant loading operations can be minimized or eliminated.[27,31,32] If these fuels are used on future satellites, the operating costs will be lowered, in some cases dramatically. Monopropellant testing of HAN-based fuels has begun to show promise and will soon be adopted for onboard propulsion systems on communications satellites and low-Earth-orbit (LEO) satellites and constellations.[21,31,32]

The formulation of HAN-based propellants is variable, based on the specific mission application and the advances in technology that may occur as the propellant and the propulsion systems are being developed.[32] A current version of the HAN-based propellant is composed of 50–61% HAN, 20–40% water, a fuel, and a number of additives to stabilize the mixture for long-term storage.[32] A formulation based on the U.S. Army Liquid Propellant Gun testing using diethyl hydroxyl ammonium nitrate (DEHAN) has been considered: 60.7% HAN, 20% water, and 19.3% DEHAN. The civil space versions of the HAN-based monopropellant will limit the use of DEHAN, and do not use tri-ethyl ammonium nitrate (TEAN), as the TEAN has been found to be incompatible with, or limits the lifetime of, some propulsion-system igniter materials. Fuels that have low or no carbon content will minimize the potential for damaging any potential catalyst igniter materials and are preferred to minimize the molecular weight of the exhaust.

Technologies for igniting the monopropellants are important. Current monopropellants use a catalytic ignition system, but some of the high-energy additives can foul the catalyst, making it less effective. Laser and combustion wave ignition are potential alternatives. Material compatibility of the monopropellants with the tank materials is also very critical for long-term space missions. Polymeric liners or chemical passivation of metallic fuel tanks may be required to alleviate this problem. The high water content of the monopropellant will create a highly oxidizing environment in the rocket chamber and nozzle. High-temperature coatings will be required to minimize the chemical attack of the exhaust on the rocket engine walls.

Advanced monopropellants are potentially simpler to handle than traditional bipropellants and have a density comparable to solid rocket motors. Figures 1 and 2 show the benefits of monopropellants for liquid rocket boosters (LRBs) for the Space Shuttle. The monopropellant shown here is tri-ethylene glycol dinitrate/ammonium perchlorate/aluminum (TEGDN/AP/Al).[34] It can reduce the overall gross liftoff weight (GLOW) of the Shuttle, and reduce the booster length, making them more compact. In Fig. 1, the GLOW of the Space Shuttle

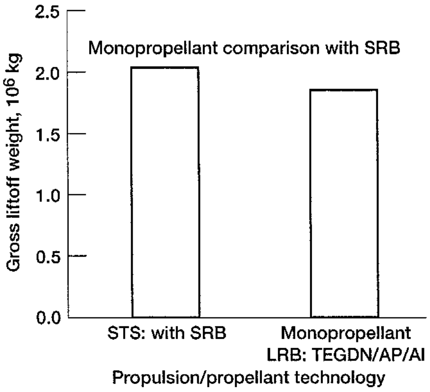

Fig. 1 Monopropellant benefits for LRBs.

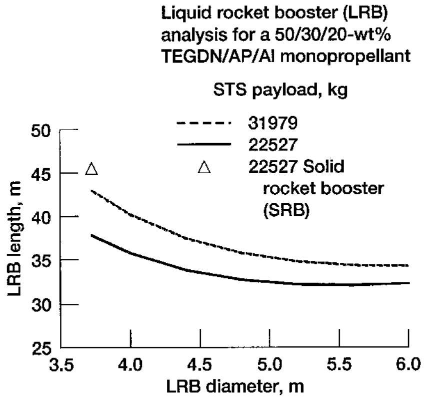

Fig. 2 Monopropellant LRBs length and diameter.

is reduced by 9.3% when using a TEGDN/AP/Al monopropellant LRB. The booster length for this option is 124 ft. By allowing the booster length to grow to 142 ft, the payload is increased from 50,000 to 70,500 lbm, and the resulting booster is still considerably shorter than the 149-ft solid rocket booster (SRB), as shown in Fig. 2. These options for increasing payload and reducing booster length give the designer more options that can lead to further reductions in vehicle mass and increases in payload performance.

Other monopropellants using gelled fuels can also improve performance and increase safety.[34] Gelled hydrogen peroxide (H_2O_2) and liquid TEGDN/AN/Al have the potential for very high density, excellent performance, and safety. Metal particles could be added to the gelled H_2O_2, further increasing its density.

Alternative Hydrocarbons

The regenerative cooling of spacecraft engines and other components can improve overall vehicle performance. Endothermic fuels can absorb energy from an engine nozzle and chamber and help to vaporize high-density fuel before entering the combustion chamber.[35–41] For supersonic and hypersonic aircraft, endothermic fuels can absorb the high heat fluxes created on the wing leading edges and other aerodynamically heated components. Dual fuel options are also possible, where the endothermic hydrocarbon fuels are used for the lower-speed portions of flight below Mach 8, and the hydrogen fuel is used for the final acceleration to the upper-stage separation velocity.[41]

Figure 3 shows the GLOW for several airbreathing space vehicles. These data are based on and derived from the analyses in Refs. 41 and 42. The baseline case is a hydrogen-fueled SSTO vehicle, whose GLOW is less than 1 million lbm.[41] While the SSTO vehicle is less massive than either of the TSTO cases, the potential for an all-airbreathing SSTO vehicle may be less likely than for a TSTO. The TSTO cases, with all hydrogen fuel and a combination of hydrogen with endothermic fuels, have GLOW values that are 1.5 and 1.7 million lbm, respectively.[42] The TSTO vehicles using endothermic hydrocarbon fuels (and H_2) will have a lower mission specific impulse and require an increased GLOW over all H_2-fueled TSTO vehicles. This increase in GLOW is relatively small at 0.2 million lbm, however, and eliminates the need for H_2 for the first stage. The higher density of the hydrocarbon fuel reduces the overall volume of the first stage, as well as enables enhanced vehicle cooling because of its heat load absorption. Several types of related hydrocarbons can increase fuel density and reduce the overall mass of the vehicle structure, tankage, and related thermal protection systems.

The amount of cooling needed in a Mach 5 aircraft was computed in Ref. 40 and the total heat load was found to be 1700 Btu/s. Over 90% of the cooling requirements were for the ramjet engine, nozzle, inlet, and other ancillary systems, with only 10% needed for vehicle air conditioning and airframe heating. Other recent aircraft studies have shown that the engine-cooling requirement may only be 50% of the heat load, with the remainder needed for onboard electronics and other vehicle subsystems.

Material compatibility is also a crucial factor in the design of these endothermic-fuel aircraft.[36] Figure 4 shows the effect of different feed-system metals on the phase change (or gasification) of aircraft fuels for cooling applications.[36] The metals noted in the figure are catalysts for improving the separation of the endothermic fuel into lighter chemical components. The lighter components can then absorb heat from the vehicle subsystems and affect the cooling of the aerodynamically heated surfaces. These design issues are particularly important for long-lived operational vehicles, such as military and civilian aircraft or reusable spacecraft.

Additional research aspects of hypersonic fuels beyond endothermic fuels are gelled cryogenic liquid fuels, recombination catalysts, fuel additives, and oxidizer capturing. Endothermic fuels and fuel additives are sought to increase the

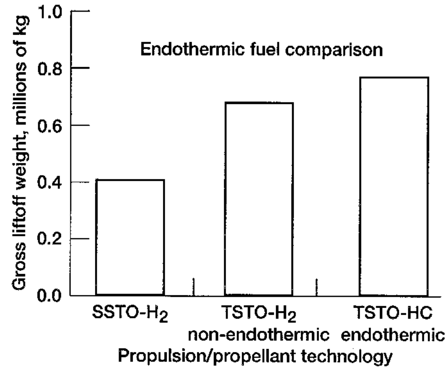

Fig. 3 Alternative hydrocarbons for airbreathing TSTO.

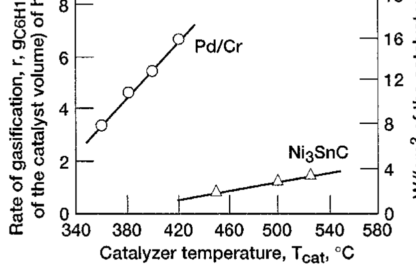

Fig. 4 Dependence of the maximal specific rate of decomposition of hexene and the energetic catalyzer productivity from the catalyzer layer temperature (pressure = 1.03 MPa).[25]

heat-sink capacity or cooling capacity of the fuel for hypersonic flight. Gelled H_2, O_2, or methane (CH_4) (with appropriate gellants, such as water, ethane, or other frozen cryogenic gellants) or nanoparticulate gellants are also of interest because of the potential for higher propellant density for airbreathing ramjet or scramjet propulsion. Fuel systems supplemented by radical recombination catalysts, such as phosphorus species, to accelerate recombination of hydrogen, oxygen, and hydroxyls (OH) to form water, with net improvement in thrust efficiency for high-speed nozzle expansions and without severe specific impulse losses, are also of interest. This research includes analytic assessments of feasibility, practical demonstrations of fuel-additive techniques using minimal, efficient, smart delivery systems, and demonstrations of thrust augmentation in nozzle test flows. Liquid air systems that can produce an oxidizer from captured air are also being investigated. The oxidizer produced from the air would be stored onboard the aircraft for later use.

Overview of Gelled and Metalized Gelled Propellants

Gelled propellants are fuels and/or oxidizers that use additives to alter their properties: Density, performance, flow characteristics, and safety.[43] Gelling a propellant allows for control of the propellant's flow properties, specifically the viscosity as a function of shear rate and its ability to stably store metal particles. With a gelled fuel, the fluid is relatively viscous in the quiescent state, but under a shear rate, as with the high velocities experienced in a propellant feed system, the fluid viscosity drops, and becomes similar to that of the ungelled fluid. As an example, gelled liquid hydrogen has a viscosity that is five times that of ungelled liquid hydrogen.[43] The gelation does not appreciably affect the liquid's boiling point, as the additive is typically only a few percent of the total fuel mass.[44–47] In the discussion of gelled and metalized gelled propellants, the amount of gellant or metal additive is expressed in weight percent (wt%). Thus, if a metalized gelled propellant, such as RP-1/aluminum, has 55-wt% aluminum, the fuel is composed of 55-wt% metal, and the remainder is the liquid fuel and the gellant. When silica is used as a gellant, there is about 41.5-wt% RP-1, and 3.5-wt% of silica.[48] Specific metal-loaded propellants can be designed for their individual applications, and many formulations are possible, each with different wt% values for the metal and gellant.[49–51]

Gelled and metalized gelled propellants have been studied analytically and experimentally for over 60 years.[4,5,43–65] Historically, work has focused on the benefits of high specific impulse, high density, and safety.[4,5,52] Current non-NASA uses for these propellants may lie in tactical and strategic missiles and aircraft ejection seats.[53–60] Extensive work has been conducted with metalized-gelled Earth-storable propellants, such as hydrazine (N_2H_4), inhibited red fuming nitric acid (IRFNA), and monomethyl hydrazine (MMH).[53–60] However, these propellants are not planned for use in future civil space-launch vehicles. To explore the potential of metalized-gelled fuels, NASA chose to pursue the propellant combinations that were more suitable to its plans, and has concentrated on O_2/RP-1 and O_2/H_2 propellant combinations and the issues related to using these gelled propellants with metal particle additives. Gelled propellants such as H_2 have also been investigated for their potential benefits in reducing boiloff, increasing density, and increasing the safety of space transfer and airbreathing aerospace vehicles.[43] Several mission studies have indicated that O_2/RP-1/Al can produce significant benefits by increasing launch-vehicle propellant density.[48,49] Mission studies for upper stages, Mars vehicles, and lunar transportation have also shown sizable benefits.[50,51]

While the benefits and military applications of Earth-storable (IRFNA/MMH) gelled and metalized gelled fuels and oxidizers are well established,[53–55] some questions still exist regarding their application for civil missions. Oxygen/RP-1/Al and cryogenic gelled and metalized gelled propellants show promise in the design studies for civil missions, assuming an engine efficiency comparable to traditional liquid fuels. In the mission studies there was a relatively limited range of efficiency where metalized propellants were most effective in reducing booster size and improving delivered payload. Experimental efforts to resolve the performance issue were therefore planned and conducted. Several questions arose prior to and during these investigations. Can propellants be fired successfully in a rocket engine? What is the combustion efficiency? Are the metalized gelled propellants easily controlled? Are their flow properties predictable? The NASA experimental work is a first step toward answering these questions. While not all of these issues have been fully addressed for all thrust levels, the data from these tests can guide future research and help pave the way for successful future testing.

Gelled Hydrogen

The benefits of gelled hydrogen have been known for many years and have experimentally proven in the past.[43–47,62] There are five major benefits: Safety increases; boiloff reductions; density increases with the attendant area and volume related mass reductions for related subsystems (thermal protection system, structure, insulation, etc.); slosh reductions; and *Isp* increases (in some cases). All of these benefits together can provide GLOW reductions for airbreathing vehicles and rocket-powered vehicles. Early tests of gelled H_2 used silica gellants, but required large weight percent values of the gellant to be successful.[47] Later work identified solid cryogenic methane and ethane, as well as nanoparticulate materials, to be more appropriate gellants for H_2.[44–46]

Specific analyses of the performance gains for various missions are dependent on the vehicle and mission design. Figure 5 shows the GLOW for a gelled O_2/H_2 (H_2 gelled with CH_4) SSTO rocket vs one using liquid O_2/H_2. The gelled H_2 SSTO rocket has a very similar GLOW, so that only a small mass penalty is paid for the benefits of the gelled H_2. This vehicle used the gelled hydrogen at a 4.2:1 mixture ratio and a 10-wt% gellant value. These analyses have not yet included the benefits of slosh reduction and boiloff reduction and their impact on reducing the vehicle GLOW and improving the overall vehicle performance. Systems analyses performed for other high-density hydrogen vehicles have shown that the reductions of the GLOW for increased density hydrogen are very significant. In cases where another high-density hydrogen, slush hydrogen, was used, the density increased by 16% and the GLOW was reduced by 10.2%, or 102,000 lbm. For airbreathing vehicles, such as the National Aerospace Plane (NASP), the estimated reduction in GLOW for slush hydrogen was from 20 to 50%. Thus, a gelled hydrogen with a 10% density increase may deliver a significant fraction of these airbreathing vehicle GLOW reductions and other subsystem mass savings. Supporting references for these analyses are provided in Ref. 42.

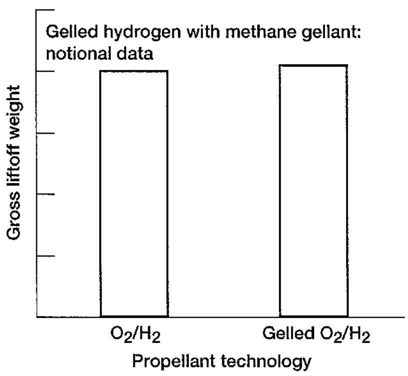

Fig. 5 Gross liftoff weight: Gelled hydrogen rocket.

Safety can be significantly increased with gelled fuels. A higher viscosity reduces the spill radius of the gelled hydrogen and limits the potential damage and hazard from a fuel spill. Another important advantage is the potential for leak reduction or elimination. The leak paths from the feed systems would be minimized and the possible explosion potential would be reduced. The extended downtime for the Space Shuttle because of hydrogen leaks has shown the high cost of spacecraft sitting idle, unable to launch their expensive cargoes.

Boiloff reduction is another feature of gelled hydrogen. The boiloff reductions are up to a factor of 2 to 3 over ungelled liquid hydrogen.[44–47] This feature will assist in the long-term storage of hydrogen for upper stages that must sustain on-orbit storage or long coast times. Also, lunar flights and interplanetary missions with large hydrogen fuel loads will derive a benefit, reducing the overall tank size by minimizing the cryogenic boiloff. Taking advantage of the boiloff reduction will require some redesign of the propellant acquisition system, as the gelled hydrogen viscosity is higher in the quiescent state. Once the hydrogen is flowing, the viscosity drops, and the thixotropic fluid is easily moved from the tank to the engine.

Significant density increases are possible with gelled hydrogen. A 10% density increase is possible with 10% added ethane or methane.[44] These gellants are introduced into the hydrogen as frozen particles that form a gel structure in the hydrogen. Figure 6 depicts the gelled hydrogen density and the rocket performance when combusted with O_2. A maximum *Isp* is attained at 5-wt% methane gellant. However, the data from previous studies show that the hydrogen should be gelled with 10-wt% of the frozen cryogen. The density of the gelled hydrogen and the rocket performance were used to estimate the "best" operating point for current rocket-powered SSTO vehicles. A design point using a 7.0:1 mixture ratio and a 10-wt% gellant level appeared to deliver the most attractive design with the lowest vehicle GLOW. This result is in contrast to the results noted earlier, and shows that no single design point is attractive for all applications. References 42 and 43 provide some additional analyses of gelled hydrogen density and performance and some additional discussion of its benefits.

Metallized Gelled Propellants

Numerous studies have shown the potential benefits of gelled fuels and oxidizers, as noted previously. Technology programs to prove the combustion performance of gelled propellants have been conducted most recently by the U.S. Army Missile Command, with its industry and university partners, for tactical missile applications. The NASA Lewis Research Center and its partners have investigated $O_2/H_2/Al$ and O_2/RP-1/Al for NASA missions and conducted experimental programs to validate elements of the combustion and fuel technology. Gelled and metalized gelled hydrogen and RP-1 have been emphasized because hydrogen and RP-1 are typical propellants for NASA launch vehicles and upper stages. Derivatives of these propellants are therefore preferred to minimize the incremental risk for a newly introduced propulsion concept.

Figure 7 illustrates an example of the GLOW reductions for O_2/RP-1/Al and NTO/MMH/Al propellants for a Space Shuttle LRB.[48,49] These analyses were conducted to find ways to increase the Space Shuttle's payload mass delivered to the space station. The payload mass and performance can be increased several ways. Booster length and diameter were important figures of merit in these studies, so as to minimize the effect on ground support and launch pad infrastructure for the Shuttle. Very significant booster-length reductions are possible with these high-density metalized fuels. These length reductions can ease the ground handling of the boosters and reduce the drag during ascent, thus improving the Shuttle's performance. Alternatively, the metalized gelled booster length can be allowed to grow to that of the SRB, and the payload performance of the Space Shuttle increases by 15% with 55-wt% RP-1/Al and 35% with 50-wt% MMH/Al. Additional increases in payload performance were possible with small diameter increases in the metalized gelled LRB. A 1-ft-diam increase (from 12 to 13 ft) would increase the Shuttle payload in LEO by from 50,000 to 70,500 lbm using 55-wt% RP-1/Al.[49]

In addition to vehicle and mission studies, experimental data have been generated to determine the rocket performance and heat transfer in metalized gelled rocket engines.[48] Combustion of a three-phase flow (solid, liquid, and gas) in the rocket engine makes heat transfer an important combustor and nozzle design issue. The results of the first experiments with 0-, 5-, and 55-wt% O_2/RP-1/Al heat transfer are shown in Fig. 8.[49] Four different fuels were tested to determine their performance: Traditional RP-1, 0-, 5-, and 55-wt% RP-1/Al. The 0-wt% case is a gelled RP-1 with no added aluminum. The engine tests used a 30-lbf thrust rocket engine. A substantial protective gelled layer formed on the injector and chamber when using a silica gellant in the 0- and 5-wt% RP-1/Al. This gelled layer caused the heat-flux reductions in the second half of the chamber, and this effect is noted particularly the 0- and 5-wt% RP-1/Al cases. The peak heat flux in the nozzle for the 5- and 55-wt% RP-1/Al were nearly double that of the baseline RP-1 fuel. The 55-wt% cases produced a metal-oxide coating on the nozzle throat, which had strong insulating properties. Improved high-temperature coatings, ablative materials, or O_2 cooling are possible avenues to accommodate these higher fluxes.

High-Energy Density Propellants

The research in high-energy density materials (HEDMs) is linked to improvements in synthetic materials, created with the most advanced chemistry and physics, that allow the largest theoretical increases in propellant density, specific impulse, or both.[25,26,66–77] These new developments in chemistry and physics have led to fuels that derive their energy from atom recombination, strained compounds, or other chemical bonds that are

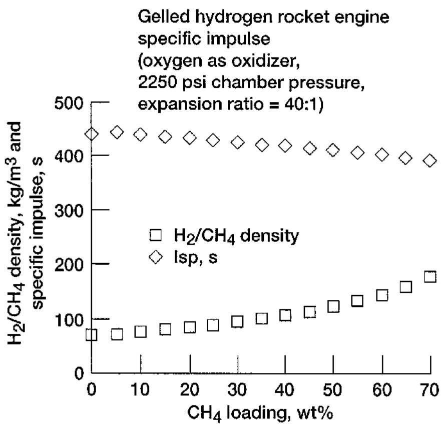

Fig. 6 Gelled hydrogen density and rocket performance.

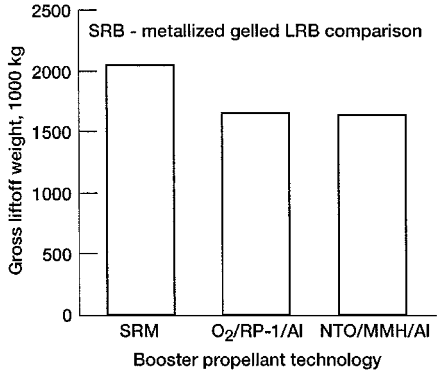

Fig. 7 Gross liftoff weights: STS with metallized gelled propellants.

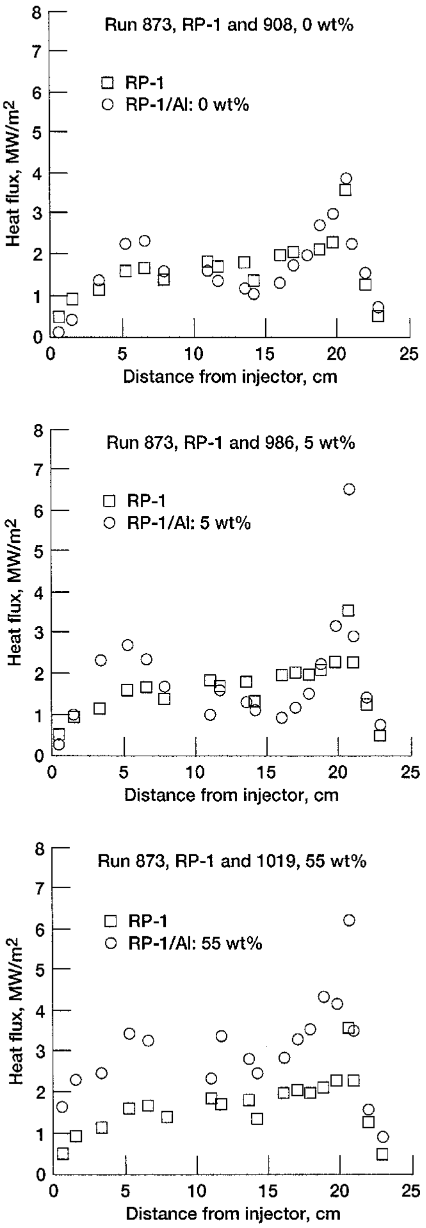

Fig. 8 Metallized gelled propellants: RP-1, 0-, 5-, and 55-wt% RP-1/Al heat transfer.

manufactured into the propellant and released only in the combustion or recombination process. Atom recombination can theoretically deliver over 1500 s of specific impulse.[66] In atom fuels employing recombination, the individual atoms are stored in a solid cryogenic matrix. Examples of the solid cryogen may be hydrogen, neon, argon, or oxygen. These theoretical performance levels are for nearly pure atomic hydrogen, which is not likely to be isolated in a practical aerospace propulsion system. Potential performance benefits in the nearer term are more likely to be in the 500–750 s specific impulse range, which require much lower percentages of atomic hydrogen: 5–15 wt%. Other very near-term fuels, such as spiro pentane and other hydrocarbons, offer 10–15 s specific impulse increases over RP-1 fuels. These increases in rocket performance can increase vehicle payloads by up to 10% or more. Cubane as an additive to hydrocarbon propellants may increase the payload of rocket systems by 10–20%.

New technologies in atom formulation and physics of material manipulation has led to the discovery and synthesis of materials that can be used in rocket propellants.[25,26,66–77] Solid cryogenic propellants storing atoms of H, Al, B, C, or other atomic additives require a unique propulsion system design in which the fuels are stored at liquid helium temperatures during ground handling and flight. Figure 9 shows the benefits of atomic hydrogen as a launch vehicle propellant and several vehicles are compared.[66] The baseline case is the National Launch System (NLS) using O_2/H_2 propellants at an I_{sp} of 430 s. The reductions in GLOW that are possible with atomic hydrogen are over 50% with a 750 s I_{sp}. This I_{sp} performance level requires 15-wt% of atomic hydrogen stored in solid H_2.

Formulation of monopropellants and bipropellants with HEDMs are taking advantage of the extensive theoretical developments of the last 50 years and turning them into realistic propellants and additives. A number of materials have been investigated, including cubane, strained ring compounds, polymeric oxygen (O_4, O_6, O_8), polymeric nitrogen (N_4, N_6, N_8), B–N analogs of prismane ($B_3N_3H_6$), and additives to cryogenic liquids and solids such as oxygen and hydrogen.[75–77] Stabilization and production of polymeric oxygen and polymeric nitrogen[26,68,73] and the formation and production of HEDMs in solid hydrogen or other appropriate solid cryogenic solids are under investigation.[69,70,75–77] Formulation of HEDMs requires the use of sophisticated computer modeling to guide the experimental production. One of the near-term processes that has been investigated is a method for large-scale cubane (C_8H_8) propellant production.

Using HEDM propellants is more complex than using traditional propellants because of their unique chemistry. While the previously mentioned monopropellants are often simpler fuels with additives that are traditional molecules that are stable in storage, the high-energy species must be formulated very meticulously because they do not occur in nature. These formulations offer increased energy density, but they must be manufactured and stored in a stabilizing medium. This medium may be solid hydrogen particles (or other cryogenic material) that surround the newly created atoms or molecules and isolate them, preventing their recombination. Figure 10 illustrates the experimental results of the formation and storage lifetime of atomic hydrogen in solid hydrogen.[25] A heat spike occurs when the atoms recombine, and it is noted in the figure when the number of atoms drops to zero. The release of a heat spike is the result of the atoms reaching a critical storage density, the point at which no more than a certain number of atoms can be stored in the solid H_2. Next-generation RLV propulsion systems can use these frozen hydrogen particles in a cryogenic liquid carrier, such as helium.[66]

Stored metal atoms in solid hydrogen may be the ultimate step in the development of higher-performance, higher-density propellants. These more advanced propellants will require longer development times, and so they would not be the first propellants to be developed or commercialized. Near-term issues related to these high-energy species might be the production methods of the atoms or species, the cryogenic feed-system components such as superinsulation, valves, and other flow control components, feed lines, cryogenic storage, and leak-detection systems.

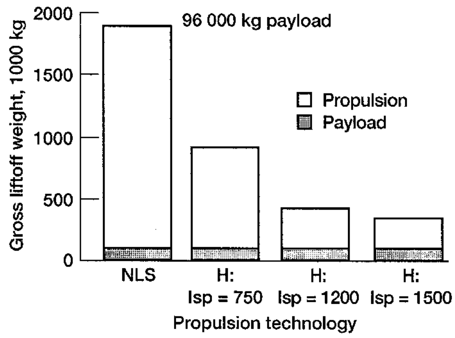

Fig. 9 Gross liftoff weights: Atomic hydrogen rockets.

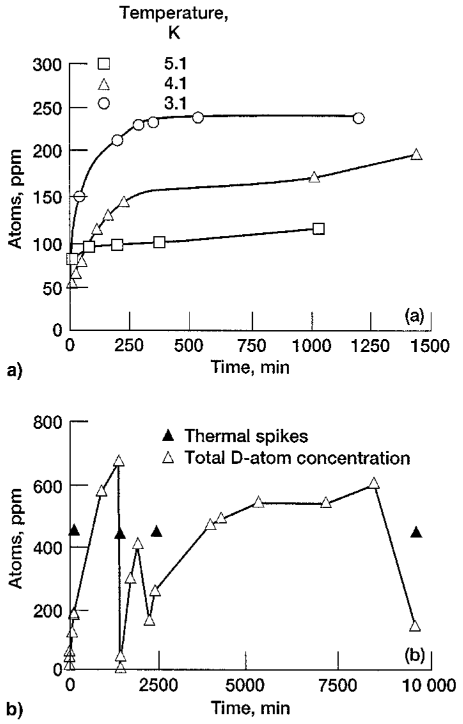

Fig. 10 High-energy density propellants: atomic hydrogen storage vs time: a) ESR measurements of T-atom concentration in D–T at three different temperatures, and b) effect of thermal spikes on total D-atom concentration as seen by electron spin resonance (ESR) in solid D2 containing 2% tritium held at 1.3 K.[25]

Concluding Remarks

Using improved propellants can lower operations cost, simplify spacecraft processing, and make space flight more accessible and affordable. Other capabilities that are enabled with these propellant technologies are better vehicle cooling, reduced cryogenic boiloff, reduced vehicle structural mass, reduced thermal protection requirements, and improved safety.

Many advanced vehicles are being planned for future aeronautics and space missions. All are able to take advantage of the extensive and well-known benefits of advanced propellants and propellant additives. Monopropellants that are safer and denser than traditional propellants can reduce space access costs. Aeronautics missions, both atmospheric and transatmospheric, can use endothermic fuels to simplify the vehicle operations and processing and allow high-speed flight without using liquid H_2. Gelled fuels can increase the density of liquid fuels, improve their safety, and reduce cryogenic boiloff and minimize fuel slosh. The addition of metal particles to the gelled fuels can further increase booster and vehicle density, giving more benefit to spacecraft designers. Future missions using HEDMs could reduce the GLOW of launch vehicles, and if the production and storage of these materials can be simplified, they may enhance or enable large fast human planetary missions. Many options for the human expansion into the solar system are possible by using advanced propulsion. Let's take advantage of propellant technologies and their potential.

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