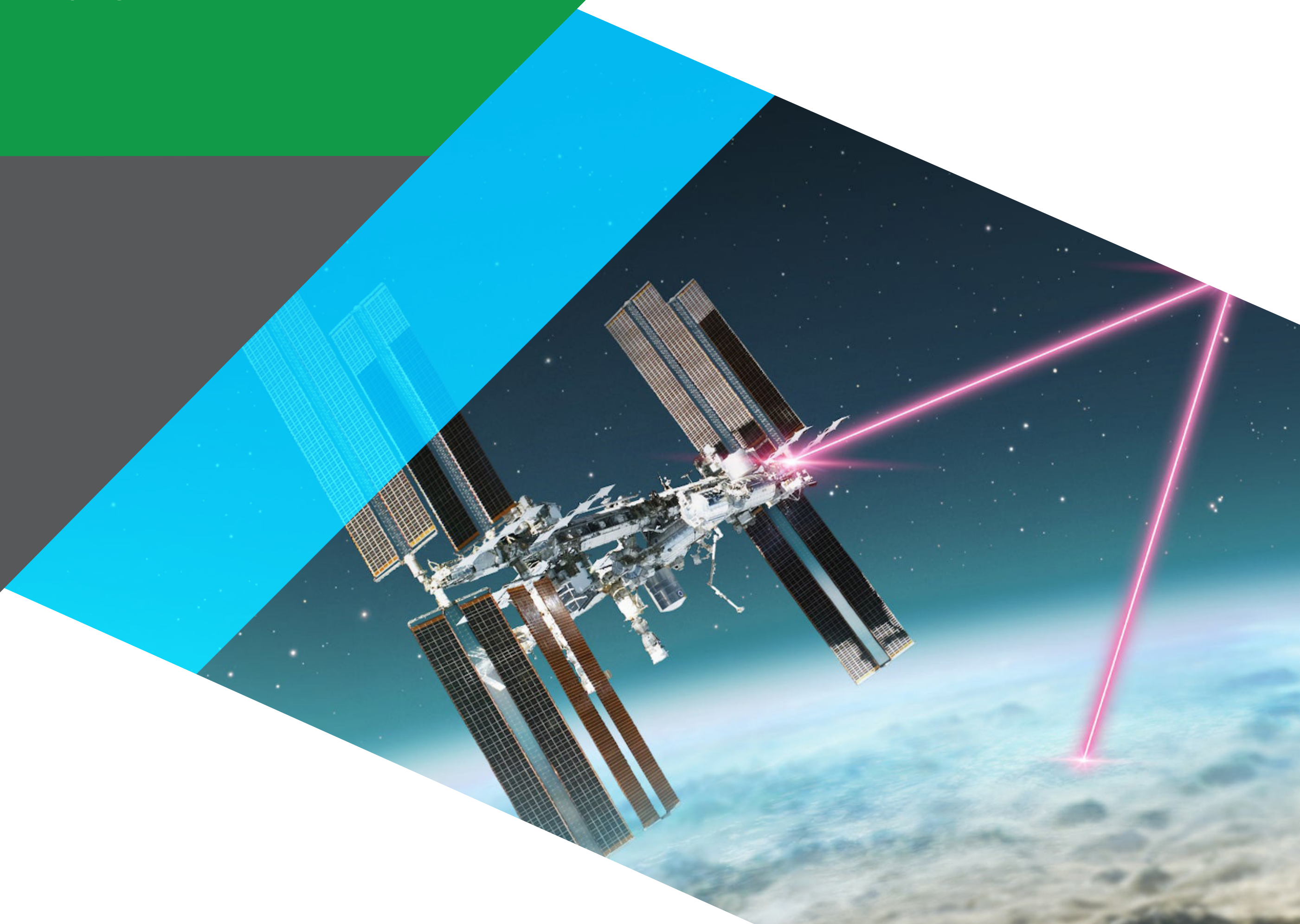
SOAR

STATE-OF-THE-ART REPORT (SOAR)
AUGUST 2023



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A MATERIALS SCIENCE PERSPECTIVE ON SPACE PROPULSION TECHNOLOGY

By Doyle T. Motes III
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DOYLE T. MOTES III

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ABSTRACT

Future conflicts are very likely to have a significant space-based component. There is a significant number of different types of satellites and spacecraft within the Earth/moon system, which are civilian, scientific, or military in origin. One of the key pieces of technology constantly being pushed for advancement is propulsion. Within the various types of engines and propulsion mechanisms are the materials behind them, both those being directly involved and those enabling the technology to function as required. If the United States is to continue its dominance in space, then research and development into the continued production of advanced materials and concepts for space propulsion must continue and be accelerated. This state-of-the-art report examines the available materials and concepts required and needed for a wide range of existing and near-term space propulsion systems to continue to enable space dominance by the United States. Many different technologies likely to see use in the near to midterm and the available materials to enable these are also discussed.

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EXECUTIVE SUMMARY

Future conflicts are very likely to have a significant space-based component. As of 4 May 2023, the website *Orbiting Now* lists a total of 7,702 satellites in various Earth orbits (not including those in transit to other bodies or in orbit of the moon or beyond). This number is expected to increase greatly over the next years as private companies and countries that have had marginal participation in spaceflight accelerate the frequencies of their launches. Of the existent craft, there are many different types of satellites and spacecraft within the Earth/moon system, which are civilian, scientific, or military in origin. One of the key pieces of technology constantly being pushed for advancement is propulsion. Within the various types of engines and propulsion mechanisms are the materials behind them, both those being directly involved and those enabling the technology to function as required.

Space propulsion addressed in this report is broken into four different families:

1. Chemical Propulsion
2. Electric Propulsion
3. Nuclear Propulsion
4. Nontraditional Propulsion

These different families of propulsion offer many potential options, including launch to space from Earth (or another celestial body, such as the moon), orbital transfers, large changes in delta-v, station keeping, and microthrusting for precision motion. However, all these different families of propulsion technologies require a wide-ranging set of materials for operation, which further directs how these technologies can be used and how research and development dollars should be spent in the future to ensure proper deployment of these technologies.

This state-of-the-art report examines the available materials and concepts required and needed for a wide range of existing and near-term space propulsion systems to continue to enable space dominance by the United States. Propulsion systems addressed in this report are at or over a National-Aeronautics-and-Space-Administration-defined technology readiness level of 6 (a fully functional prototype or representational model). Many different technologies likely to see use in the near to midterm and the available materials to enable these are also discussed.

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SECTION 01 INTRODUCTION TO SPACE TECHNOLOGY

Space, especially the near-space frontier, is becoming increasingly important to world powers. The space domain is integral to military, politics, civilian life, and science. In addition, with the proliferation of continued missions to space, orbits are becoming crowded and contested. Space exploration began in the post-World War II era, and the space race of the 1960s and 70s saw major advancements in space exploration technology. From the launch of the first satellite, Sputnik, humans have sent hundreds of thousands of objects into space [1]. Today, space technology allows for communication, navigation, surveillance, scientific research, and space exploration by both government and civilian entities. The use of space technology is built directly into the global infrastructure and is therefore vitally important to maintain, advance, and protect.

1.1 THE SPACE FRONTIER

By continuing to operate in space and expand its space presence, the United States faces many challenges. First, the United States is not the only nation trying to expand its use of space technology. Nations and commercial entities around the world are increasingly entering the space domain for matters of infrastructure, government, and military support. Satellites are currently the single most essential piece of technology in space and are creating an increasingly denser blanket of objects circling the Earth. Finding room for an ever-growing number of satellites is a significant problem, but, more importantly, it creates the additional issue of space debris and debris fields. As satellites are decommissioned or suffer collisions and are broken apart, the remaining debris is collected in a field encircling the Earth. According to a report from the Defense Intelligence Agency (DIA), "more than 25,000 objects of at least 10 cm in size were tracked and cataloged in Earth's orbit" by 2022 [2] (see Figure 1-1 for a graphic example). Avoiding these objects can be an issue for space-bound vehicles, and deorbiting these objects is another separate issue.

Beyond Earth's orbit, the United States is looking to develop capabilities for manned missions on the moon and, eventually, beyond. The National Aeronautics and Space Administration (NASA) is actively sponsoring projects developing new technologies for its Moon-to-Mars mission, which aims to establish infrastructure on the moon that can be used for research and, eventually, as a launch platform for missions to Mars in future decades [3]. In addition to NASA's interest in the moon and Mars for research, it is possible the United States or other nations could explore the use of the moon for government and military purposes [4]. Developing interplanetary capabilities is an inevitable next step in the longer-term goals for research and space exploration. It is possible these missions could eventually face similar pressures as those operating in Earth's orbit from expansion and competition by other actors. Reaching near-Earth targets and being able to establish an indisputable presence will require more advanced and affordable technologies that allow for faster, longer, more sustained, and possibly repeated uses.

Note: Image may not be exact to scale

Figure 1-1. European Space Agency (ESA) Computer Rendering of the Space Debris Field Around Earth *(Source: ESA [5])*.

1.2 GLOBAL SPACE CAPABILITIES

More nations are looking to expand their space capabilities for military and government purposes. The DIA published an updated report in 2022 titled "2022 Challenges to Security in Space: Space Reliance in an Era of Competition and Expansion," originally published in 2019, which outlines the state of current global space activity and the potential challenges and threats posed to continuing operations. Many foreign entities, including U.S. adversaries, have increased their space presence. In particular, China has more than doubled its total in-orbit satellites from 2019 to 2021 [2]. This increased competition to establish domain above and around Earth may lead to conflict, and, due to the nature of the technology being used in space, foreign assets make for enticing targets for an offensive assault.

Antisatellite (ASAT) weapons are actually as old as satellites. When Sputnik launched in 1957, the United States responded by launching a ballistic missile at it [6]. Developing ASATs is considered a necessity to denying space, and these weapons can have a range of effects, from simply jamming/scrambling electromagnetic (EM) signals to completely destroying a foreign asset [2]. However, these weapons are not necessarily specially designed space weapons. Generally speaking, any weapons that could be used against prime space targets (satellites mostly) would be "dual use," such as intercontinental ballistic missiles (ICBMs), hypersonic missiles, directed-energy weapons, electromagnetic pulse (EMP) weapons, etc. [7, 8]. Space debris itself can even be used as a means for destruction or disruption. Intentionally sacrificing a state-owned satellite to crash into a foreign satellite would impact foreign intelligence, surveillance, and reconnaissance capabilities and create a greater field of debris that could further disrupt other satellites and future space operations (this scenario of increasingly generated space debris is called the Kessler Syndrome [6]).

Space has historically been regarded as a peaceful, research-focused frontier, open to cooperative exploration. As space becomes more commoditized and the value of using space technology increases for government and military agencies, this attitude is destined to change. While treaties and agreements have been made among different global organizations to protect the sanctity of space, their posterity is not guaranteed [9]. In the face of increasing competition and potential threats, it is important to understand U.S. and other foreign space capabilities and their respective abilities to deny space.

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SECTION 02 MATERIALS PERSPECTIVE ON PROPULSION TECHNOLOGY

The space environment is dramatically different than the environment within the protective atmosphere of the Earth. The lack of an atmosphere means that there is no drag that can be leveraged to stabilize satellite paths and rotations. Radiation and the presence of charged particles are a constant threat that necessitates the use of specially designed electronics and components. A lack of gravity means that debris or gas does not fall away from a spacecraft but travels along with it.

The end effect is that systems and, therefore, their materials, do not behave the same in space as they would on Earth. In addition, test facilities that can replicate the space environment do not exist on Earth, meaning materials must be developed and tested on Earth before being used in space, providing further complications. Significant work is therefore expended to be able to construct and utilize materials that can address and operate effectively within these challenges.

Materials development is a key area for space propulsion and technologies enabling space propulsion. For the purposes of this report, the author has chosen to organize based on the primary means of propulsion as defined by NASA's Glenn Center (see Figure 2-1) [10]. This includes the following subject areas:

- Chemical Propulsion Technologies
- Electric Propulsion Technologies
- Nuclear Propulsion Technologies
- Nonpropellant-Based Propulsion Technologies

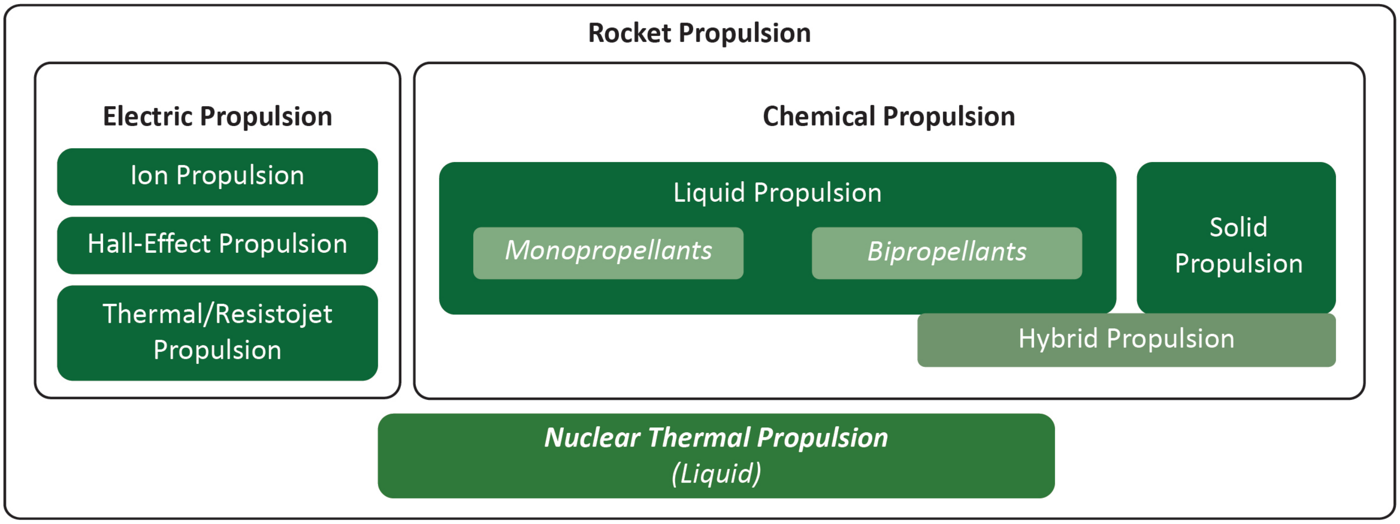


Figure 2-1. Tether Braking Hooks to Achieve Safe Payout Used on the TEPCE Cubesat Mission *(Source: Defense Systems Information Analysis Center [adapted from J. Banks {11}]).*

2.1 CHEMICAL PROPULSION TECHNOLOGIES

Rocket engines use stored propellants as reaction masses to create high-speed propulsive jets of fluid, usually high-temperature gas. They are reaction engines, producing thrust by ejecting mass. Chemical rocket engines use the combustion of reactive chemicals to supply the necessary energy. Rocket vehicles carry their own oxidizer, meaning they can be used in the vacuum of space as a means of propulsion for spacecraft and ballistic missiles. The ideal exhaust gas is hydrogen, the lightest of all elements, but chemical rockets produce a mix of heavier species, reducing the exhaust velocity.

2.1.1 Technology Development/Descriptions

There are several types of rockets: solid-fuel (or propellant) rocket, hybrid rocket, liquid-fuel (or propellant) rocket, dual-mode propulsion rocket, and tripropellant rocket. In recent days, NASA has made news with the testing of a rotating detonation rocket engine [12].

2.1.1.1 Solid-Propellant Rockets

A solid-propellant rocket (solid rocket) is a rocket engine using solid propellants (fuel/oxidizer). Some of the earliest forms of rockets were solid-fuel rockets powered by gunpowder and used by the Arabs, Chinese, Persians, Mongols, and Indians as early as the 13th century.

Since solid-fuel rockets can remain in storage for extended periods without significant propellant degradation, they launch in a reliable fashion, meaning they are frequently used in military applications such as missiles. Solid propellants have lower performance compared to liquids and, thus, are not often used as the primary propulsion in modern medium-to-large launch vehicles customarily used to orbit commercial satellites and launch major space probes. Solid-propellant rockets are frequently used as strap-on boosters to increase payload capacity or for spin-stabilized add-on upper stages when higher-than-normal velocities are required (such as for NASA's space shuttle).

2.1.1.2 Hybrid-Propellant Rockets

A hybrid-propellant rocket is a rocket with a rocket motor that uses liquid/gas and solid rocket propellants. Hybrid rockets avoid some of the disadvantages of solid-propellant rockets like the dangers of propellant handling but avoid the mechanical complexity of liquid-propellant rockets. Because it is difficult for the fuel and oxidizer to be mixed completely, hybrid rockets tend to fail more benignly than liquids or solids. Like liquid rocket engines, hybrid rocket motors can be shut down easily and the thrust is throttleable. Hybrid systems are more complex than solid ones, but they avoid significant hazards of manufacturing, shipping, and handling solid rocket motors (SRMs) by storing the oxidizer and the fuel separately.

2.1.1.3 Bipropellant Rockets

A bipropellant rocket engine is a rocket engine using two propellants (often liquid propellants), which are kept separated and reacted in another separate chamber to produce a hot gas to expand for propulsion. Liquid-bipropellant systems require precise mixture control but are often more efficient than solid or hybrid rockets. Bipropellant rockets are more complex and expensive than solid or hybrid rockets, particularly when turbopumps are used to pump the propellants into the chamber. However, these rockets permit the use of comparatively lightweight tankage and vehicle structure. Some types of liquid-propellant rockets or hypergolic (self-igniting) rocket fuels may also fall into this category.

2.1.1.4 Tripropellant Rockets

A tripropellant rocket is a rocket using three propellants. Tripropellant systems can be designed to have high specific impulse and have been investigated for single-stage-to-orbit designs. While tripropellant engines have been tested by

Rocketdyne and Energomash, no tripropellant rocket has been flown. Types of liquid-propellant rockets can fall into this category.

There are two different kinds of tripropellant rockets. One is a rocket engine that mixes three separate streams of propellants (using a high-density metal additive, like beryllium or lithium, with existing bipropellant systems), burning all three propellants simultaneously. The other kind of tripropellant rocket is one that uses one oxidizer but two fuels, burning the two fuels in sequence during the flight (burning dense fuels first, then lighter ones).

2.1.1.5 Liquid-Propellant Rockets

A liquid-propellant rocket uses high-density liquids as fuel, which allows the volume of the propellant tanks to be relatively low. Lightweight centrifugal turbopumps are also used to pump the rocket propellant from the tanks into a combustion chamber, allowing the propellants to be kept under low pressure.

An inert gas stored in a tank at a high pressure is sometimes used instead of pumps in simpler small engines to force the propellants into the combustion chamber. These engines may have a higher mass ratio but are usually more reliable and are therefore used widely in satellites for orbit maintenance.

Liquid rockets can be monopropellant rockets using a single type of propellant or bipropellant rockets using two types of propellant. Some designs are throttleable for variable thrust operations, and some may be restarted after a previous in-space shutdown. Liquid propellants are also used in hybrid rockets, with some of the advantages of a solid rocket. Monopropellants and nonreactive propellants are sometimes included in this category, but the authors have chosen to separate them for the purposes of this report.

2.1.1.6 Air-Liquid Engines

A liquid air cycle engine (LACE) is a type of spacecraft propulsion engine used for launch that attempts to increase its efficiency by gathering part of its oxidizer from any atmosphere present (this type of engine is not an option for launch from the moon or Mars). It uses liquid-hydrogen (LH_2) fuel to liquefy the air.

Conceptually, a LACE works by compressing and then quickly liquefying the air. Compression is achieved through the ram-air effect in an intake similar to those on a high-speed aircraft (like the SR-71 Blackbird), where intake ramps create shockwaves that compress the air. The LACE design then blows the compressed air over a heat exchanger containing flowing LH_2 to rapidly cool and liquify the oxygen (O_2) and nitrogen (N_2).

To significantly reduce the liquid-oxygen (LO_X) launch mass, a LACE vehicle needs to spend more time in the lower atmosphere to collect enough oxygen to supply the engines during the remainder of the launch. This leads to greatly increased vehicle heating and drag losses, which therefore increases fuel consumption to offset the drag losses and the additional mass of the thermal protection system (TPS). The engineering trade-offs involved are quite complex and highly sensitive to the design assumptions made.

Most significantly, the LACE system is far heavier than a pure rocket engine with the same thrust, and the performance of launch vehicles of all types is particularly affected by increases in vehicle dry mass (such as engines) that must be carried all the way to orbit, as opposed to oxidizer mass that would be consumed in flight.

LACEs were studied to some extent in the United States during the late 1950s and early 1960s in support of a winged spaceplane. However, as NASA moved to ballistic capsules during Project Mercury, funding for research into winged vehicles slowly disappeared, and LACE work along with it. LACEs were also the basis of the engines on the British Aerospace Horizontal Take-off and Landing (aka HOTOL) design of the 1980s, but this did not progress beyond system studies.

2.1.1.7 Monopropellant Rockets

Monopropellants consist of chemicals that release energy via exothermic chemical decomposition, usually through use of a catalyst. While typically stable under defined storage conditions, monopropellants decompose very rapidly under certain other conditions to produce a large volume of hot gases available to perform mechanical work. The most common monopropellant is hydrazine (N_2H_4). Other "green" monopropellants are being investigated by a number of different entities (both in the United States and outside, such as the ESA).

2.1.1.8 Nonreactive-Propellant Engines

A nonreactive-propellant engine (commonly called a cold-gas thruster or a cold-gas propulsion system) uses the expansion of a (typically inert) pressurized gas to generate thrust via the reaction force of the gas expanding through a nozzle. These systems have been in use since the 1950s with thrust levels varying from fractions of a pound to tens of pounds. They are typically used for small delta-v (Δv) or when a small total impulse is required, such as for attitude control of small spacecraft. Cold-gas thrusters do not involve any chemical reactions, resulting in a lower thrust and efficiency compared to conventional monopropellant and bipropellant rocket engines. Theoretically, their design can simply consist of a fuel tank, a regulating valve, a propelling nozzle, and required plumbing. They are considered one of the cheapest, simplest, and most reliable propulsion systems available for orbital maintenance, maneuvering and attitude control.

Advantages of cold-gas thrusters include:

- No combustion takes place. This allows the thrusters to be used where a regular rocket engine would be too hot and eliminates the need for thermal management systems.
- They are relatively simple, small, inexpensive, and less prone to failures than complex engines.
- Most of the propellants they use are safe to handle both before and after firing the engine. Inert fuel can be used, making it very safe and acceptable for CubeSat use.
- They do not build up a net charge on the spacecraft and require very little electrical energy to operate (usually only the operation of the opening/closing valve).
- Their lifetimes in space after launch and deployment are measured in years.
- They can be operated in pulse-width modulation mode.

Disadvantages of cold-gas thrusters include:

- They cannot produce a high thrust such as combustive rocket engines.
- They are less efficient than traditional rocket engines.
- The maximum possible thrust is dependent on the pressure in the storage tank. Unless more sophisticated systems are installed, the pressure in the tank and the maximum thrust possible decrease (this can be addressed by using liquified gases as the gas volatilizes to produce thrust so the pressure in the tank is maintained, but this leads to additional issues).

In particular, CubeSat propulsion system development has been predominantly focused on cold-gas systems, as CubeSats have strict regulations against the use of pyrotechnics and hazardous materials for propulsion purposes. As of 2020, the online "Nanosats Database" [13] reports that over 1,300 nanosatellites and CubeSats have achieved orbit (this does not necessarily mean they are still in orbit). Of all the launched CubeSats, only ~5% have propulsion modules. Of these, only limited information is publicly available on the actual performance and the success of their thrusters in flight.

Therefore, technology development for cold-gas thrusters has focused on development of new propellants that offer better performance under certain scenarios or that offer mission-specific advantages compared to traditional cold-gas thruster propellants or system upgrades that can reduce mass or otherwise provide an advantage to the propulsion system in question.

2.1.2 Chemical Propulsion Materials Issues and Technology Needs

There are many items that drive materials design and use in chemical rocket engines including the type of fuel (if it is solid or liquid) and, more recently, if the rocket is reusable or expendable. Here, the focus is on:

- Propellants of Different Types
- Thermal Protection Materials
- Structural Material Components (Such as Motor Casing and Nozzles)
- Specifics for Air-Liquid Engines

2.1.2.1 Liquid Propellants

Liquid propellants can be categorized as oxidizers and fuels and as monopropellants and bipropellants (made up by the oxidizer plus the fuel and combusted to heat the gas). Some oxidizers and fuels can act either as part of a bipropellant system or as a monopropellant. Monopropellants generate propulsive energy through the exothermic decomposition of a single-component liquid or formulated mixture of fuel and oxidizer. This engine type allows the use of relatively simple system design but results in low performance.

The most commonly used storable liquid fuels are rocket propellant-1 (RP-1) (also known as refined propellant-1) and hydrazine and its derivatives (hydrazine is specifically discussed later in this report). RP-1 is a highly refined version of kerosene that is used in conjunction with LO_X in launch stages because of its combination of high density, low toxicity, and reasonable performance.

Hydrogen is the most common liquid fuel, existing for launch purposes cryogenically. It provides high performance and is an excellent regenerative coolant. However, at its normal boiling point of 20 K, it has a low specific gravity and requires heavy insulation and large tanks. Large tanks become a materials-and-design concern due to the small size of the molecule and its propensity to leak (such as the delays in the 2022 Artemis launch). This means that appropriate sealing and sealing materials must be used (specifically those that are stable at the fuel's cryogenic temperatures). In addition, the thick insulation (lightweight foam) on the cryogenic tanks caused problems for the Space Shuttle Columbia's STS-107 mission, as a piece broke loose, damaged its wing, and caused it to break up and be destroyed on re-entry. It is especially favored for high-performance, expander-cycle, upper-stage engines.

For missiles that will sit in storage for long periods, such as missiles stored in vertical launch systems on ships, ICBMs, and spacecraft in orbit requiring significant amount of Δv, storing cryogenic propellants over extended periods is awkward, unreliable, and expensive. Because of this, propellants such as hydrazine or solid rocket engines are preferred. In addition, hybrid rockets have recently been the vehicle of choice for low-budget private and academic forays in aerospace technology.

Research needs in this area include low-temperature sealing and better insulation (here, better is determined to be very lightweight and have a very low thermal conductivity). In addition, better adhesive mechanisms that address the unique environment around insulating cryogenic hydrogen that can keep insulation pieces in place are always being sought.

Thousands of combinations of fuels and oxidizers have been tried over the years, along with thousands more that are in various stages of development. Such an extensive topic as this may justify its own state-of-the-art report in the future. Some of the more common and practical propellant material types include the following.

- LO_X and LH_2: Examples include the space shuttle main engines; Ariane 5 main stage and the Ariane 5 evolved cryogenic, model A (ECA) second stage; the first stage of the Delta IV; and the upper stages of the Saturn V, Saturn IB, Saturn I, and Centaur rocket.
- LO_X and Kerosene/RP-1: Examples include the Saturn V; Zenit rocket; R-7 Semyorka family of Soviet boosters, including the Soyuz, Delta, Saturn I, and Saturn IB first stages; Titan I; and Atlas rockets. The Merlin's engines on the SpaceX Falcon 9 use an LO_X/RP-1 combination propellant (see Figure 2-2). Channels are etched into the nozzle to allow radiative cooling to prevent the material from melting during use.

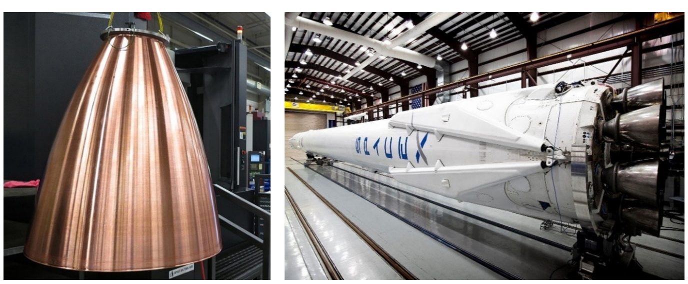


Figure 2-2. Images of the SpaceX Merlin Engine *(Sources: Creative Commons [14] [Left] and Flickr Commons [15] [Right]).*

- LO_X and Ethanol (Ethyl Alcohol [C_2H_5OH]): Examples include early liquid-fueled rockets, such as the V-2 rocket used by the Germans in World War II to bomb Great Britain. This fuel continues to be used but has seen more development into hypergolic derivatives for enhanced stabilization.
- LO_X and Liquid Methane: The most relevant example of this engine is SpaceX's Raptor engines (as seen in Figure 2-3) designed for the heavy-lift Starship system.

Figure 2-3. SpaceX's Raptor Engine (Left) and Test Firing in McGregor, TX (Right) *(Sources: Wikimedia Foundation, Inc., [16] [Left] and Flickr Commons [17] [Right]).*

A sub-branch of these propellants is hypergolic propellants. Hypergolic propellants are rocket-propellant material combinations where the components spontaneously ignite when they come into contact with each other. The two propellant components usually consist of a fuel and an oxidizer. The main advantages of hypergolic propellants are that they can be stored as liquids at room temperature and that engines powered by them are easy to ignite reliably and repeatedly.

Other examples (some of which are hypergolic) include:

- LO_X and Gasoline (C_8H_{18}): Robert Goddard's first liquid-fuel rocket.
- T-Stoff (80% Hydrogen Peroxide [H_2O_2] as the Oxidizer) and C-Stoff (Methanol [Methyl Alcohol {CH_3OH}]) and Hydrazine Hydrate ($N_2H_4 \bullet n$) (Water [H_2O] as the Fuel): Walter Werke HWK 109-509 engine used on the German Messerschmitt Me 163B Komet, a rocket-type fighter aircraft used toward the end of World War II.
- Nitric Acid (HNO_3) and Kerosene: An example of this propellant's use is the Soviet Scud-A (SS-1).

- Inhibited Red-Fuming Nitric Acid (IRFNA) Nitric Acid + Dinitrogen Tetroxide (N_2O_4) and Unsymmetric Dimethylhydrazine (UDMH) ($[CH_3]_2N_2H_2$): This is used on the Soviet Scud-B, -C, and -D (aka SS-1-c, -d, and -e).
- Nitric Acid With Dinitrogen Tetroxide (Mixed as 73% and 27%, Respectively, Called AK27) and Kerosene/Gasoline Mixture: This was used in various Soviet Cold War era ballistic missiles by Iran (Shahab-5) and by North Korea (Taepodong-2).
- Hydrogen Peroxide and Kerosene: Used by the United Kingdom in the 1970s as part of the Black Arrow effort.
- Aerozine 50 (Which Is 50/50 Hydrazine and UDMH) and Dinitrogen Tetroxide: A hypergolic combination, this was used in Titans 2–4, the Apollo lunar module, the Apollo service module, and interplanetary probes (examples include Voyagers 1 and 2).
- UDMH and Dinitrogen Tetroxide: This is a hypergolic combination. Examples include the Soviet Proton rocket and various other Soviet rockets.
- Monomethylhydrazine (MMH) ($[CH_3]HN_2H_2$) and Dinitrogen Tetroxide: A hypergolic combination, this was used on the Space Shuttle Orbital maneuvering system engines.

2.1.2.2 Monopropellants

Monopropellants consist of chemicals that release energy through exothermic chemical decomposition, usually through use of a catalyst. These substances are stable when stored but decompose very rapidly under controlled conditions to produce a large volume of expanding gas capable of performing thermodynamic work.

Hydrazine

The most commonly used monopropellant for in-space propulsion is hydrazine. Hydrazine is a colorless, fuming, oily liquid with an ammonia-like odor. It is also highly toxic and carcinogenic, meaning leaks on Earth or in space can put astronauts or technicians at serious risk. Hydrazine is highly corrosive and can easily damage unprotected surfaces, ranging from certain metals to human flesh. In addition, its breakdown products are also toxic and corrosive. Due to its toxicity and corrosive nature, hydrazine requires special equipment to use and procedures to transport and handle, increasing the complexity of any system that it is used in. From an economic perspective, hydrazine is expensive to produce, handle, and transport. It is a very energetic and reactive material, making it uniquely suitable for use as a propulsion material [18].

Hydrazine exists in a constant state of decomposition. The attack of storage materials by hydrazine is usually only considered a problem for nonmetals, although contaminants (such as carbon dioxide [CO_2] and chlorine gas [Cl_2]) have been added and can produce problems (such as chloride attack on steel). In general, the greater concern is that a metallic storage media will accelerate the decomposition of the hydrazine. For nonmetals, catalytic and material attack must be considered. As a result of these facts, significant research has been directed to develop alternative monopropellants to hydrazine, some of which have begun to be used.

Green Monopropellants

Nosseir et al. [19] provided a comprehensive literature review on the state of the art of green monopropellants. There are a number of green monopropellants becoming available that can provide for high Δv missions (such as lunar missions). These are broken into the following classes:

- Energetic Ionic Liquids (EILs)
  - Hydroxylammomium Nitrates (HANs)
  - Ammonium Dinitrimides (ADNs)

- Liquid Nitrous-Oxide (NOx) Monopropellants
- Hydrogen-Peroxide Aqueous Solutions (HPASs)

EILs. EILs (or premixed oxidizer/fuel ionic-propellant blends) consist of oxidizer salts (called ionic liquids [ILs]) mixed with ionic fuel or molecular fuel, forming a premixed propellant (i.e., EIL monopropellant, as widely referred to among the rocket propulsion community) [20]. The addition of the fuel component reduces the high adiabatic flame temperature of the IL mixture, further stabilizing the combustion process. Typically, methanol is used to control the burning rate of the monopropellant while ammonium nitrate (NH_4NO_3) is used as a stabilizer [21].

EILs can be used for impulsive high-thrust-demanding orbital maneuvers, but the main challenge is size requirements. If used on a CubeSat or similar system, there is a necessity for component miniaturization. One EIL, the Advanced Spacecraft Energetic Nontoxic (ASCENT) monopropellant (a HAN monopropellant developed by the U.S. Air Force [USAF] that was formerly known as AF-M315E), has been tested in space on 1 N and 22 N thrusters through the Green Propellant Infusion Mission launched in 2019 [22]. One disadvantage several latest state-of-the-art green propellants have are relatively high flame temperatures, which can cause severe catalyst degradation, making it difficult to rapidly manufacture cost-effective and simple thruster designs, especially for the micro/nanosatellites. To address this, additive manufacturing (AM) has been used to permit the use of high-temperature alloys, such as Ti6Al4V (Ti64) and In 625 (a Ni-Cr superalloy), with melting points of approximately 1,625 °C and 1,300 °C, respectively [23, 24].

In addition, catalytic decomposition of ASCENT requires higher preheating temperature, compared to hydrazine [25], and the catalyst bed preheating nominal start temperature is 315 °C [26].

Another option is LMP-103S, which is an ADN-type monopropellant. LMP-103S has a very high energy content and can be stored for more than 20 years. It has been shown to be insensitive to space radiation [27].

Finally, SHP163 was tested in space in the Green Propellant Reaction Control System utilizing a 1 N class thruster in the RAPIS-1 satellite launched in 2019 by the Japanese Aerospace Exploration Agency (JAXA).

Green electric monopropellant (GEM) is a HAN-based EIL, containing HAN, AN, (2,20-dipyridyl), (1,2,4-triazole), 1H-pyrozol, and water [28]. GEM is a proprietary of Digital Solid-State Propulsion Company [26] and is developed as a superior replacement for AF-M315E [29]. Its main advantage is that it can be ignited electrically and does not need a catalyst bed.

NOx-Based Propellants. NOx-based propellants offer properties capable of functioning for small satellites or high-thrust in-space propulsion up to nearly 600 N. The literature mentions a test campaign with a 600 N thruster to achieve a specific impulse of 259 s [30]. However, an issue reported during this study was a high combustion temperature, which requires a complex engine design and active cooling system. In addition, the NOx fuel blend is likely incompatible with titanium, meaning specific material systems are required for containment and storage. Advantages of NOx fuel blends include their nontoxic and noncarcinogenic nature, low freezing point, higher specific impulse than hydrazine, and self-pressurization capabilities, which allow for simple feed-system and tank-pressurization-system design.

NOx-based propellant combination development is being led by commercial companies Dawn Aerospace, Impulse Space, and Launcher. The first NOx-based system ever flown in space was by D-Orbit onboard their ION Satellite Carrier in 2021, using six Dawn Aerospace B20 thrusters.

HPAS. HPAS has been leveraged from chemical rocket development, meaning the fuels are stable and safe and have relatively high reliability. For applications with fewer restrictions over size constraints, high-concentration hydrogen-peroxide propellants can operate either as a monopropellant or hypergolically ignite in bipropellant systems. Hydrogen peroxide is not compatible with 400 series stainless steels, but it is compatible with aluminum, and titanium experiences only slight degradation. In this way, materials are available to store and use this fuel. As mentioned previously, the means to quickly manufacture components (such as AM) are a critical driver here. Table 2-1 shows relevant monopropellants compared to hydrazine.

Monopropellant Catalysts

Catalysts are used as ignition mechanisms for monopropellants. Since monopropellant combustion reactions can reach >800 °C (depending on the catalyst system used), catalyst materials with low melting temperatures, those that lose substantial strength with temperature, or those that are not suitable for use as a catalyst cannot be used to initiate the decomposition reaction. In addition, it is desired for a catalyst to be able to be used at temperatures below 35 °C (permitting immediate use in the case of emergencies), otherwise known as a spontaneous catalyst. Iridium, the most common catalyst, is one of the 9 least-abundant stable elements in Earth's crust, having an average mass fraction of 0.001 parts per million in the crust (as points of reference,

Table 2-1. Selected Monopropellants Developed for Use in Space Propulsion

Monopropellant	Type	Max I_{sp} (s)	Density (g/cm^3) @20 °C	Vol. I_{sp} (s/cm^3)	Adiabatic Flame Temp (K)	Freezing Point (°C)	Toxicity
Hydrazine	Pnictogen Hydride	239	1	239	1170	1.5	High
ASCENT	HAN-Based EIL	266	1.47	391	2166	<–80	Low
SHP163	HAN-Based EIL	276	1.4	386	2401	<–30	NA
HNP221	HAN-Based EIL	241	1.22	294	1394	<0	NA
HNP225	HAN-Based EIL	213	1.16	247	990	<–10	NA
LMP-103S	HAN-Based EIL	252	1.24	312	1903	NA	Moderate
GEM	HAN-Based EIL	283	1.51	427	Unknown	NA	Low
FLP-103	ADN-Based EIL	254	1.31	333	2033	NA	NA
FLP-106	ADN-Based EIL	255	1.36	345	2087	NA	NA
FLP-107	ADN-Based EIL	258	1.35	349	2142	NA	NA
N_2O (Liquid)	Liquid NOx	206	0.75	154	1913	NA	Low
Nitromethane	Liquid NOx	289	1.14	329	2449	NA	Low
NOFBX	Liquid NOx	350	0.7	245	3200	NA	NA
H_yNOx (Ethene)	Liquid NOx	303	0.88	266	3264	NA	Low
NOx/Ethanol	Liquid NOx	331	0.89	295	3093	<–80	Low
Type 85	HPAS	151	1.34	206	893	–17	NA
Type 90	HPAS	172	1.4	239	1019.3	–12	NA
Type 98	HPAS	186	1.43	266	1222	–2	NA

Note: NA = property is not available, H_yNOx = hydrocarbons mixed with nitrous oxide.

platinum is 10 times more abundant, gold is 40 times more abundant, and silver and mercury are 80 times more abundant than iridium). Iridium is most commonly found in meteorites and in the Earth's crust at the K-T boundary, which is believed to have been produced by the meteorite that struck the Earth 65 million years ago and was largely responsible for the extinction of the dinosaurs.

Work has been undertaken to increase the number of catalysts available. One example discusses using ruthenium and tungsten carbide in a subscale catalytic engine [31]. The results showed that the ruthenium catalyst lost as much as 20% of its mass via erosion, underlining one of the key challenges to developing a successful monopropellant catalyst.

In summary, the biggest issues driving catalyst development from a materials perspective are:

- Cost/Supply
- Erosion Resistance
- Ability to Initiate Reaction at Low Temperatures
- Ability to Maintain Relevant Material Properties at High Temperatures

2.1.2.3 Nonreactive Propellants

Cold-gas thrusters utilize nonreactive propellants. This is a mature technology, but there are two areas that are being examined by researchers looking to optimize systems for mission-specific requirements: (1) the propellant (gas) and (2) the supporting systems.

Various gases have been used as propellants, the most popular being nitrogen, oxygen, hydrogen, and helium. The major advantage of helium and hydrogen is their much higher specific impulses. However, helium and hydrogen are small molecules, increasing the chances of leakage and resulting in a very low density (e.g., a larger, heavier storage tank is needed to store the same propellant mass) [32]. In general, nitrogen has been a common propellant of choice for many missions—it is inert, the molecules are not so small as to result in leaks (such as is often seen for hydrogen), it is abundant and low cost, and it provides an acceptable specific impulse. In general, research in recent years has focused on materials that can be deployed as compressed liquids to leverage total impulse capacity advantages over gaseous or multiphase saturated propellants. Within this category, propellants that can be stored at lower tank pressures than nitrogen (which usually requires tens of megapascals of pressure) are sought. However, this introduces other problems, including gas/liquid mixing in the tankage (sloshing) from microgravity conditions [33].

Refrigerants have been investigated for years for use as propellants. One project from 2012 with the University of Missouri at Rolla investigated using R134a in its two-phased regime as a propellant [34, 35]. R134a has been banned in some countries, and, by 2021, all newly manufactured light-duty vehicles in the United States will no longer use R134a [36]. However, for use in space and on spacecraft, it is considered inert and safe. Dual fluid refrigerants (again, R134a) have been investigated to take advantage of the larger, possible total impulse for a low tank pressure and using only a small tank volume [37, 38].

Other propellants examined address the problem of gas/liquid separation in space (sloshing) and leveraging the ability to store propellant in liquid form (low pressure) while still achieving a high specific impulse is naphthalene [39]. An image of this design is shown in Figure 2-4.

Another proposed solution to this issue is solid elemental iodine [40]. Iodine was examined for use as an alternative to xenon due to problems with cost and difficulty in obtaining the material. Iodine's main drawback is its electronegativity, with a high chemical affinity to most of the commonly used structural materials in aerospace industry. However, this can be bypassed by

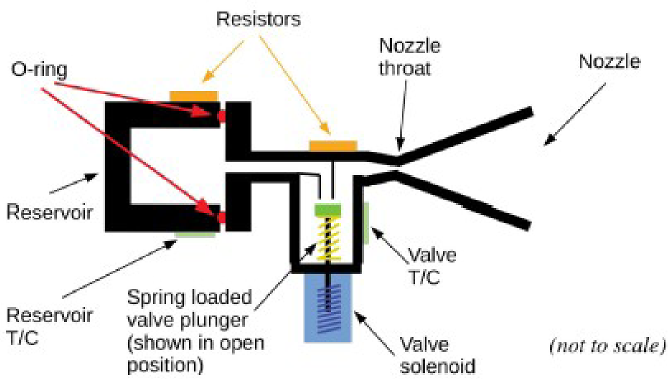


Figure 2-4. A Diagram of a Naphthalene Cold-Gas Thruster With Its Main Components Highlighted *(Source: Tsifakis et al. [39]).*

carefully selecting the elements in the system and performing an assessment of the corrosion and deposition of iodine, as several authors have also mentioned. Martinez et al. examined 25 material candidates for the tank-and-flow control system, selected a material, and tested it, but do not mention the material used. This mission was launched on Xiaoxiang1-08, a 6U CubeSat in November 2019.

For support systems, the majority of the technology is mature and used for tankage, plumbing, and valves (known materials systems, most often aluminum and titanium alloys). One area where modern materials science can help address optimization is in nozzle design and manufacturing. AM has been used to create the entire thruster system (tank, pipes, and nozzles) out of a single piece. Examples of this include the BioSentinel mission, successfully launched 16 November 2022 [41], and the INSPIRE spacecraft (not yet launched) [42, 43]. The cold gas used was DuPont R236fa. The use of three-dimensional (3D) printing also allows the optimization of space for increased propellant storage (165 g). The thrust from each nozzle is 50 mN with a specific impulse of 31 s [44]. AM has been used to manufacture mission-specific nozzles and is well suited to address issues specific to a wide range of materials/technologies and what needs to be done to improve/solve the issues.

2.1.2.4 Solid Propellants

SRMs contain several different propellant families that can then be molded into a particular shape of interest depending on the burn rate and launch scenario (see Figure 2-5 for a notional image of a solid-propellant rocket).

Black-Powder-Based Propellants

Black powder (gunpowder) is composed of charcoal (fuel), potassium nitrate (KNO_3) (as the oxidizer), and sulfur (as both a fuel and catalyst). It is one of the oldest pyrotechnic compositions used in rockets. In modern times, black powder is used in low-power model rockets, as they are cheap and easy to produce. The fuel grain is typically a mixture of pressed, fine powder (into a solid, hard slug), with a burn rate that is highly dependent on composition and operating conditions. The grain is sensitive to fracture and, therefore, catastrophic failure. This type of rocket cannot produce significant amounts of thrust and is likely not a candidate for space propulsion.

Zinc-Sulfur-Based Propellants

Zinc-sulfur-based propellants are composed of powdered metallic zinc and powdered sulfur (oxidizer). This type of propellant is composed of micrograins that are pressed together. This propellant does not find many practical applications outside specialized amateur rocketry due to its poor performance (most of this propellant burns outside of the combustion chamber) and fast linear burn rates. It is most often employed as a novelty propellant, as the rocket accelerates extremely quickly, leaving a spectacular, large orange fireball behind. Again, for these reasons, this type of rocket is not suited for space propulsion.

Sugar "Candy-" Based Propellants

Sugar (or rocket candy) propellants are an oxidizer (typically potassium nitrate) and a sugar fuel (typically dextrose [$C_6H_{12}O_6$], sorbitol [$C_6H_{14}O_6$]),

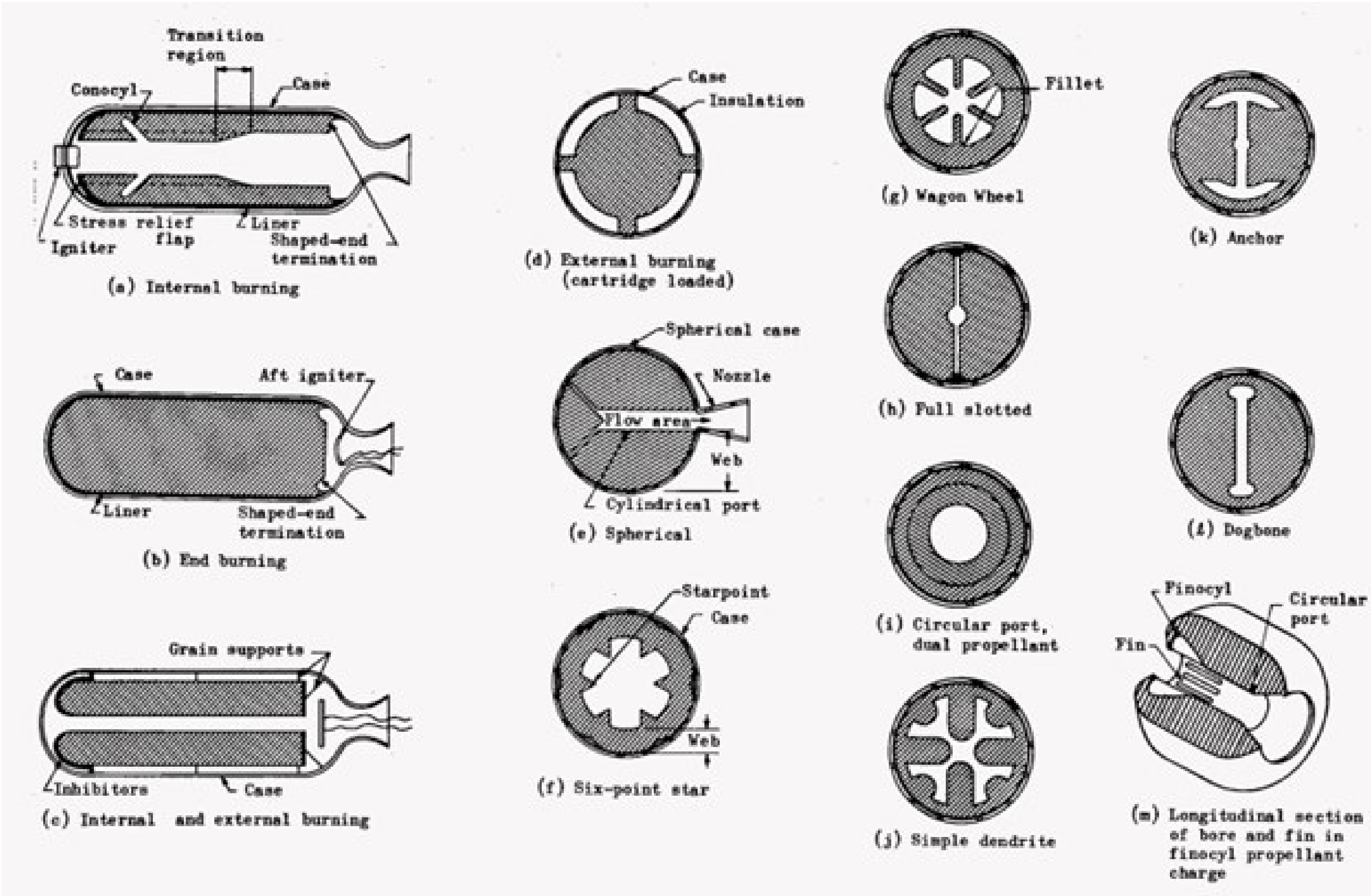


Figure 2-5. Components of an SRM *(Source: NASA [45])*.

or sucrose [$C_{12}H_{22}O_{11}$]) that are cast into shape by gently melting the propellant constituents together and pouring or packing the material into a mold. Candy propellants generate a low-medium, specific impulse and are primarily used by amateur and experimental rocketeers. For these reasons, this type of rocket is not suited for space propulsion.

Double-Based (DB) Propellants

DB propellants are composed of two monopropellant fuel components. One of these typically acts as a high-energy (yet unstable) monopropellant, and the other acts as a lower-energy and stabilizing (and gelling) monopropellant. A common example is nitroglycerin dissolved in a nitrocellulose gel and solidified with additives. DB propellants are implemented in applications where minimal smoke is required yet a medium-high specific impulse is required. The addition of metal fuels (such as aluminum) has been found to increase performance.

Composite Propellants

Composite propellants are often used as solid propellants in space propulsion systems. A powdered oxidizer and powdered-metal fuel are mixed and held together with a rubbery matrix binder (that also acts as a fuel). Composite propellants are often either ammonium-nitrate based or ammonium-perchlorate based (NH_4ClO_4). Ammonium-nitrate-composite propellant often utilizes magnesium/aluminum fuel and offers medium-range performance. Ammonium-perchlorate composite propellant (APCP) often uses aluminum fuel and delivers high performance. Aluminum is the most common fuel choice, as it has a reasonable, specific energy density and a high-volumetric energy density and is difficult to accidentally ignite. Composite propellants are cast and retain their shape after the rubber binder hydroxyl-terminated polybutadiene (HTPB) cross links (solidifies) with the aid of a curing agent. Because of its high performance, moderate ease of manufacturing, and moderate cost, APCP is widely used in relevant space and military rockets. Ammonium-nitrate-composite propellant is cheaper and less efficient, meaning it is more often used by hobbyists. Ammonium dinitramide ($NH_4N[NO_2]_2$) is being considered for use as a 1-to-1 replacement for ammonium perchlorate to offer a chlorine-free substitute in composite propellants. Unlike ammonium nitrate, ammonium dinitramide can be substituted without a loss in motor performance.

Polyurethane-bound aluminum solid fuel is used in Polaris ICBMs. APCP used in the space shuttle solid rocket boosters used an ammonium perchlorate (oxidizer, 69.6% by weight), aluminum (fuel, 16%), iron oxide (Fe_2O_3) (a catalyst, 0.4%), polybutadiene acrylonitrile polymer (a nonurethane rubber binder and a secondary fuel, 12.04%), and an epoxy curing agent (1.96%). The 2005–2009 NASA Constellation Program (a previously cancelled crewed spaceflight program) was to use a similar polybutadiene-acrylonitrile-bound APCP.

In 2009, a group succeeded in creating a propellant of water and nanoaluminum (aluminum ice [aka ALICE]) [46]. This propellant could be synthesized in situ (due to the presence of water ice and alumina [Al_2O_3]) on many space targets (including lunar targets and near-Earth asteroids).

High-Energy Composite Propellants

Typical high-energy composite propellants start with a standard composite propellant mixture (such as APCP) and add a high-energy explosive into the mix. This extra component usually is in the form of small crystals of royal demolition explosive (also known as hexogene [$O_2N_2CH_2]_3$) or high-melting explosive (HMX) (also known as octogen [$C_4H_8N_8O_8$]), both of which have a higher energy than APCP. Despite a modest increase in specific impulse, implementation is limited due to the hazards of high-explosive additives.

Composite-Modified, Double-Base Propellants

Composite-modified, double-base propellants start with a nitrocellulose/nitroglycerin double-base propellant as a binder and add solids (typically ammonium perchlorate and powdered aluminum) normally used in composite propellants. The ammonium perchlorate makes up the oxygen deficit introduced by using nitrocellulose, improving the overall specific impulse. The aluminum improves the specific impulse as well as combustion stability. High-performing propellants, such as NEPE-75 (containing polyethylene glycol, which makes the mixture significantly more physically flexible) are used to fuel the Trident II D-5 ballistic missile and replace most of the ammonium perchlorate found in composite propellants with polyethylene-glycol-bound HMX, further increasing the specific impulse. The mixing of the composite and double-base propellant ingredients has become quite common.

Minimum-Signature (Smokeless) Propellants

One of the most active areas of solid-propellant research is the development of high-energy, minimum-signature propellant using China Lake compound #20 (CL-20) (hexanirtohexaazaisowurtzitane [$C_6H_6N_6\{NO_2\}_6$]) nitroamine, which has 14% higher energy (by mass) and 20% higher energy density than HMX. This new propellant has been successfully developed and tested in tactical rocket motors (such as vertical-launch systems on guided-missile destroyers). This propellant is nonpolluting, acid free, solid particulate free, and lead free. It is also smokeless and has only a faint shock-diamond pattern visible in the otherwise transparent exhaust. This is of interest to the military due to the bright flame and dense smoke trail produced by the burning of aluminized solid propellants, which introduce the risk of giving away launch positions. CL-20 propellant has yet to be deployed widescale due to the costs associated with its production.

Electric Solid Propellants

Electric solid propellants are a family of high-performance plastisol (a colloidal dispersion of small polymer particles in a liquid plasticizer) solid propellants that can be ignited and throttled by the application of an electric current. Unlike conventional rocket motor propellants that are difficult to control and extinguish, electric solid propellants can be ignited reliably at precise intervals and durations. No moving parts are required, and the propellant is insensitive to flames or electrical sparks. This type of propellant is also being considered for use in explosives required for mining and for pyrotechnics. To the authors' knowledge, it has not yet been employed in a rocket.

Solid-Propellant Shapes

While not an inherently material property, solid rocket fuel is cast into specific shapes to produce certain burn rates. Solid rocket fuel deflagrates from the surface of exposed propellant in the combustion chamber. The geometry of the propellant inside the rocket motor therefore also dictates motor performance. As the surface of the propellant burns, the shape evolves (a subject of study in internal ballistics), most often changing the propellant surface area exposed to the combustion gases. Examples of such performance is shown in Figure 2-6 for different core configurations.

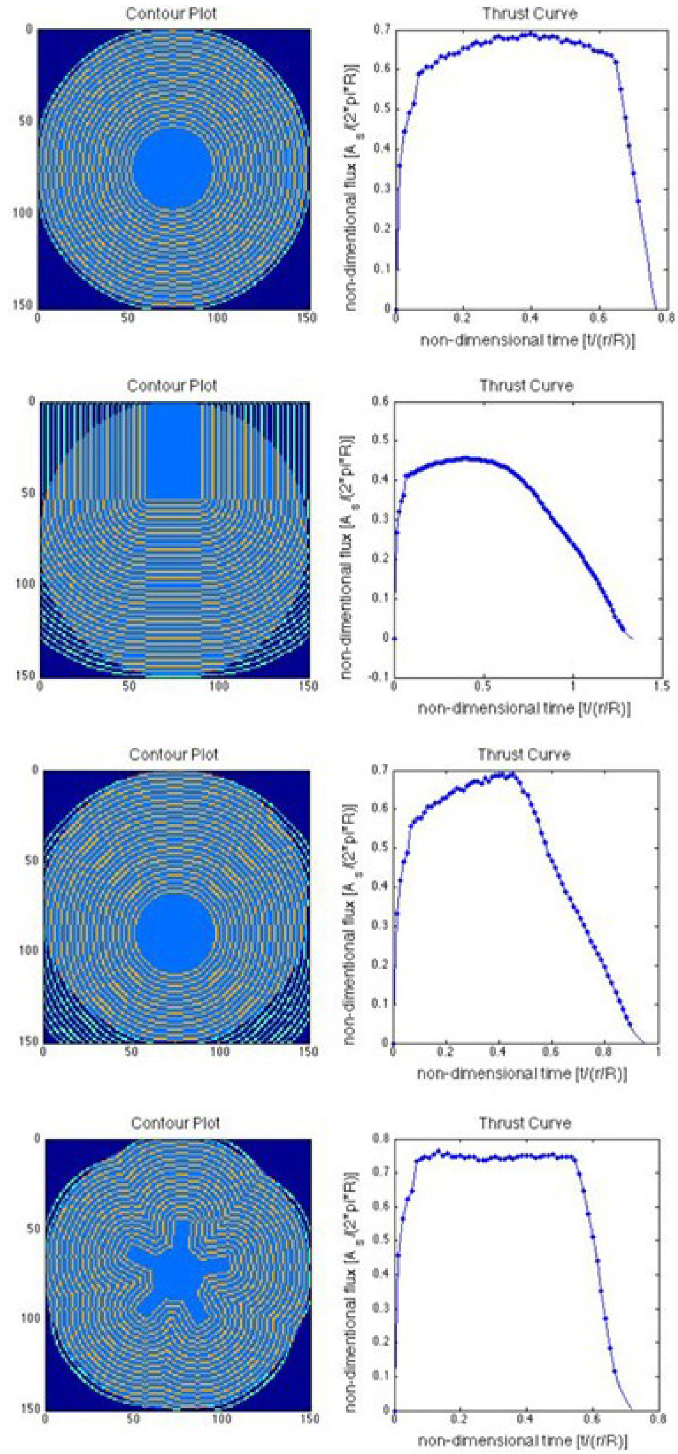


Figure 2-6. Examples of the Results of Geometric Configurations for Solid-Fuel Rockets: Circular Bore Simulation (Top), C-Slot Simulation (Middle Top), Lunar Burner Simulation (Middle Bottom), and Five-Point Finocyl Simulation (Bottom) *(Source: Orr [47])*.

Solid-Propellant Manufacturing Methods

A solid-propellant rocket contains a rocket engine using solid propellants (fuel/oxidizer). The earliest rockets were solid-fuel rockets powered by gunpowder; they were used in warfare by the Chinese, Indians, Mongols, and Persians as early as the 13th century.

Casting. The solid-propellant portion of hybrid rocket fuel grains is manufactured via casting techniques since they are typically a plastic or a rubber. Complex geometries, which are driven by the need for higher fuel mass flow rates, make casting fuel grains for hybrid rockets expensive and time consuming due in part to equipment costs. On a larger scale, cast grains must be supported by internal webbing so large chunks of fuel do not inadvertently come loose and impact or even potentially block the nozzle (causing rocket failure). Grain defects (often voids or clusters of voids) are also an issue in larger grain systems. Traditional fuels that are cast are HTPB and paraffin waxes.

Leveraging AM. AM is an active research area and is currently being used to create grain structures and macropropellant shapes that were otherwise not possible to manufacture. Helical ports have been shown to increase fuel regression rates while also increasing volumetric efficiency (a visual reference example of this is shown in Figure 2-7). An example of material used for a hybrid rocket fuel is acrylonitrile butadiene styrene (ABS) plastic, a material that is commonly used for fused deposition modeling 3D printing (and also the material that LEGO are made of). The printed material is also typically enhanced with additives to improve rocket performance. Recent work at the University of Tennessee, Knoxville has shown that, due to the increased surface area, the use of powdered fuels (i.e., graphite, coal, and aluminum) encased in a 3D-printed ABS matrix can significantly increase the fuel burn rate and thrust compared to traditional polymer grains [48, 49].

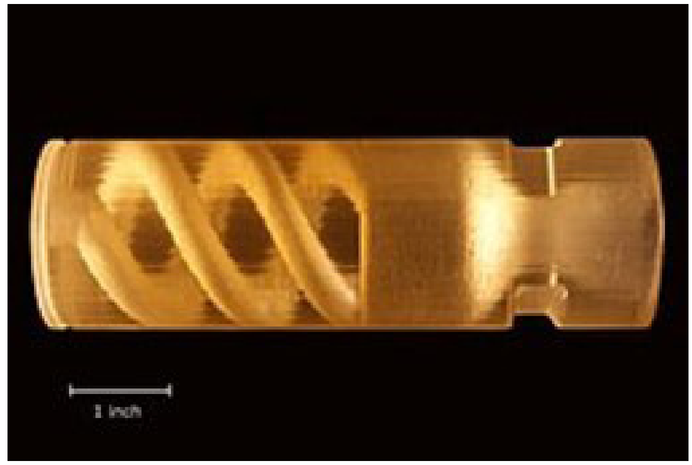


Figure 2-7. A Transparent Portable Education Demonstrator 3D-Printed Hybrid Rocket Fuel Grain With Dual Helical Fuel Ports, a Postcombustion Chamber, and a de Laval Nozzle, Shown Prior to Hot Fire Test *(Source: Steiner [50])*.

Quality Control

The presence of voids within solid-propellant castings can result in rocket failure if chunks of propellant break from the main piece and become lodged in the nozzle. X-ray-computed tomography, low-power ultrasonic testing, and low-power-microwave (EM) nondestructive testing are used as a means of quality control after fabrication and to ensure that propellant does not degrade after long storage.

Hybrid Rocket Propellants

Hybrid-propellant rockets use a combination of liquid and solid propellants. Some liquid-fuel options are kerosene, hydrazine, and LH_2. Common solid fuels for a hybrid rocket engine include polymers such as acrylics, polyethylene, cross-linked rubber (e.g., HTPB or synthetic rubber), or liquefying fuels (e.g., paraffin wax). Plexiglass has been used as a fuel, with the added benefit that combustion can be observed through a visibly transparent combustion chamber. HTPB is currently the most popular fuel for hybrid rocket engines for two reasons: (1) its high, internally stored energy and (2) the handling safety it offers to users (tests have been performed in which HTPB was soaked in LO_x and still did not react). The solid fuels are generally not as dense as SRM propellants, so they are often doped with aluminum to increase the density and, therefore, the rocket performance.

2.1.2.5 Motor Casings

Motor casings may be constructed from a range of materials (examples of which are shown in Table 2-2 and reproduced from Rajesh et al. [51]). Work on this topic was started in the early days of the Space Age as part of the designs of the Polaris and Minuteman missile systems [52].

The casing must be designed to withstand the pressure and resulting stresses of the rocket motor, possibly at elevated temperatures. For design, the casing is considered a pressure vessel. The casing consists of the pressure vessel portion, the cap. Aluminum is commonly used for motors where appropriate. An aluminum-lithium alloy is used for the Falcon 9 (SpaceX), as this alloy is fairly robust from a mechanical-strength perspective and has a lower density than many other aluminum alloys due to the addition of the lithium. Steel was used for the space shuttle boosters. Filament-wound graphite epoxy casings are used for high-performance motors (such as for Firefly Aerospace's liquid-fueled rockets). To protect the casing from corrosive hot gases, a sacrificial ablative thermal liner is often installed on the inside of the motor casing.

A similar materials selection group exists for the cap—aluminum alloys, steels, or carbon-fiber-reinforced polymer (CFRP), depending on the pressure requirements (SpaceX uses a CFRP cap for the Falcon 9).

Future materials of interest here revolve around a further reduction in density (to drive mass down even further), which, for metals, may involve the use of lighter-weight alloying elements. An exemplar material is AlBeMet AM162, which is an aluminum-beryllium metal matrix composite (MMC) that has a density of 2.071 g/cm^3 (pure aluminum has a density of approximately 2.7 g/cm^3). This aluminum-beryllium MMC combines the high-modulus and low-density characteristics of beryllium with the fabrication and mechanical behaviors of aluminum. An advantage of this

Table 2-2. Different Materials and Their Applications in Rocket Casings

Material	Application
Low Case Carbon Steel (15 CDV6)	Used in SRM Case
Maraging Steel (M250)	Used in Booster SRM Case
Ti6Al4V	High-Pressure Gas Vessels
Aluminum Alloys (AA 2219, AA 2014, AA 6061)	Liquid-Propellant Tanks, Engine Components
Magnesium/Magnesium-Lithium Alloys	Upper-Stage Structures (Payload Adapter, Avionics Deck, Equipment Bay Structure)
Carbon/Kevlar-Fiber Epoxy Resin	Casing, Pressure Vessels, Inner Stages, Payload Adapter
Carbon-Fiber/Silicon-Carbide Ceramic Matrix	Nose-Cap of Heat Shield, Leading Edges and Control Surfaces (if Applicable)
Silicon-Carbide Fibers/Silicon-Carbide Ceramic Matrix Composite	High-Temperature/Hot Structures

material is that the parts can be manufactured with the same techniques normally used for aluminum, meaning that special tooling is not needed. The material is safe to handle when not being worked on, but the carcinogenic properties of the beryllium mean that special precautions must be taken to avoid exposure during machining with respiratory protection needed where dust could be formed.

For CFRPs, work is being done to develop thermoplastic carbon-fiber composites (which are different from thermoset carbon-fiber composites). Thermoplastic composites can be recycled after they are deemed no longer safe for further use, whereas no reuse chain exists for thermoset composites.

2.1.2.6 Thermal Protection

For rockets where the propellant burns for long periods (such as those associated with the initial stages of a launch), the burning propellant is kept from burning through the casing by thermal liners, a form of a TPS. They shield the motor casing undergoing ablation (thermal decomposition under high temperature [pyrolysis]) of the organic constituents that form the char layer. The ablated layer acts as a barrier against the high mass and heat transfer during solid-propellant combustion. During the ablation process of a TPS, three main zones are formed (as shown in Figure 2-8).

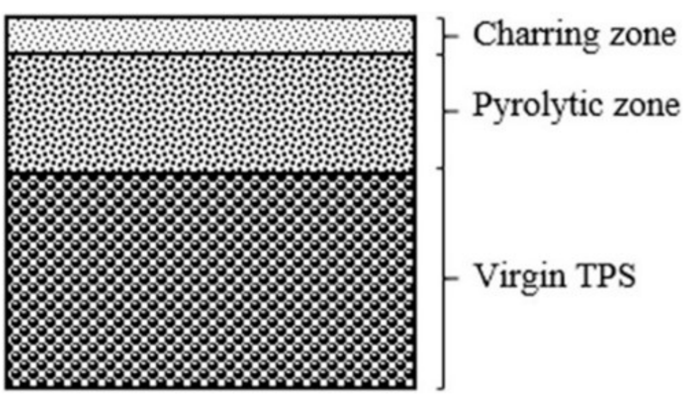


Figure 2-8. The Three Main Regions Formed During the Ablation Process *(Source: Amado et al. [53])*.

Elastomeric materials are often used as the heat-shielding materials including ethylene propylene diene rubber (EPDM), nitrile-rubber based, and silicone based, with polyurethane-based materials becoming more popular in recent years [53]. Fibers/fillers are used to create TPS composites. Examples of materials from Amado et al. [53] by matrix material are shown in Tables 2-3–2-5.

Amado et al. [53] also discuss how new materials are continuously under development, particularly in composites of rubber materials with nanofibers and, to a lesser extent, with nanoparticles. The use of graphite with rutile and modified fumed silica has been reported, with a wide range of property modifications available. The use of various reinforcements opens wider possibilities for obtaining efficient elastomeric heat shield materials. Arabgol et al. [54] used fumed silica, organoclay, and short carbon fibers in acrylonitrile butadiene rubber, achieving ablation rates comparable to those obtained with EPDM or even lower. Nanocomposites based on polyetherimide (ULTEM™ 1010) with nanoclay as filler and flame-retardant additives have displayed enhanced ablation and thermal properties, rendering ablation rates as low as 0.07 mm/s for a heat flux of 100 W/cm^2. Other novel materials are polyphosphazenes, even though these materials are expensive and not extensively available.

2.1.2.7 Nozzles

Nozzles come in two types. The first is a traditional nozzle, a de Laval nozzle, and includes a convergence, throat, and divergence. In the rocket industry, these regions are usually labeled as the thrust chamber, which includes the combustion within the chamber and the throat (and some of the expansion after that). The nozzle is the further diverging section after that. The second type has regeneratively cooled thrust chambers and nozzles, which are ubiquitous in launch and space vehicles.

Table 2-3. Fillers for Use in TPS Materials for EPDM Matrix Material

Material	Ablation Rate (mm/s)	Thermal Conductivity (W/m K)	Tensile Strength (MPa)	Elongation (%)	Thermal Properties (TGA)
0–50% phr KF/EPDM	0.13–0.18	0.013–0.018 (calculated)	2–13	175–300	464–474 °C
Control—MWCNT/EPDM	0.078–0.092	—	6.28–7.84	385–483	$T_{10\%}$ is 29% Higher Than Control
Aramid Fiber-Silica-Zinc Oxide/EPDM	0.11/0.12	—	—	—	TGA 465 °C
15 phr Kevlar/EPDM	0.03	—	—	—	—
Virgin EPDM, No Additives or Compounding	0.29–0.72 (Different Erosion Conditions)	—	—	—	—
20% phr KP + 5% Alumina + 5% Silica + 40% Dechhlorane + 20% Antimony Trioxide/EPDM	0.1	0.21	8.5	16	500 °C Maximum Weight Loss
Aramid Fiber-PR-Mineral Oxide/EPDM	—	—	4.15	45	Maximum Loss 350 °C
20% Wollastonite/EPDM	Maximum Temperature for OAT Test 202 °C/ 5 mm	—	3.8	195	Maximum Weight Loss 480–500 °C
Sepiolite/EPDM – Silica/ Natural Rubber EPDM	0.177/0.40 (Control)	—	1.2–1.5	15	First Transition 360–450 °C
30 phr KP/EPDM	0.015	0.171	9.35	11.7	—
Kevlar/EPDM, Composition Not Disclosed)	0.151	—	1	700	53.45% Loss at ~400 °C
25 phr Carbon Fiber/ 25 phr KP/EPDM	—	0.198	11	7.4	27% Original Mass
Silicon Dioxide/EPDM	—	0.202	5.2	350	—

Note: phr = parts per hundred resin, KF = Kevlar filled, MWCNT = multiwalled carbon nanotube, KP = Kevlar pulp, PR = plastic rubber, NR = natural rubber, OAT = oxyacetylene torch, $T_{xx\%}$ = temperature at which xx% weight loss occurs.

de Laval Nozzles

Traditional rocket nozzles consist of a chamber and a throat. The main requirement of a rocket nozzle material is to ensure the overall nozzle retains dimensional integrity and does not degrade by erosion of any exposed internal surfaces or cracking. It must be able to function in the presence of high flame temperatures, chamber pressures, and the chemical reactivity of the combustion gases. Materials examined and commonly used are refractory metals, refractory-metal carbides, graphites (amorphous graphite or carbon-carbon), ceramics, cermets, and fiber-reinforced plastics.

Table 2-4. Fillers for Use in TPS Materials for Polyurethane Matrix Material

Material	Ablation Rate (mm/s)	Thermal Conductivity (W/m K)	Tensile Strength (MPa)	Elongation (%)	Thermal Properties (TGA)
20–50 phr KF/EPDM	—	0.363	—	—	—
5% Nanoclay//HTPB-PU	0.42–0.69	n.d.	1.07//1.47	700//650	—
5% phr Perlite/HTPB	0.7	—	1.22	130	—
POSS-PU	0.22–0.39	—	—	—	T5% 260–285 °C
HTPB-Based PU	0.346	—	—	—	PHRR 1,037 kW/m^2
23% POSS/HTPB-Based PU	0.298	—	—	—	PHRR 632 kW/m^2
10% Cloisite® 30B/TPUN	—	0.2 (PU Matrix)	—	—	80% Weight Loss at 400 °C
5% Closite® 30B/TPU	—	0.4	—	—	450 °C Main Loss (10 °C/min); Mass Remaining 2–5%*
16% Alumina/HTPB-Based PU	0.13	0.3	1.877	411	—
5–15% Nanoclay/Antimony Trioxide (Sb_2O_3) 70-80% Weight Loss	0.169–0.199	0.25–0.4	—	—	382–488 °C

Note: TGA = thermogravimetric analysis, PU = polyurethane, POSS = polyhedral oligomeric silsesquioxane, PHRR = peak heat-release rate, TPUN = thermoplastic polyurethane elastomer nanocomposite, TPU = thermoplastic polyurethane.

Table 2-5. Fillers for Use in TPS Materials for Nitrile Rubber Matrix Material

Material	Ablation Rate (mm/s)	Thermal Conductivity (W/m K)	Tensile Strength (MPa)	Elongation (%)	Thermal Properties (TGA)
0% MMT/NBR// 10% MMT/NBR	0.087//0.075	0.156//0.151	2.58//2.54	157//151	TGA Maximum Weight Loss at 411–474 °C
0% PR/NBR-50%/NBR	0.235/0.095	—	—	—	First loss 264.7/263.8 °C
Silica and Carbon Phenolic/ HNBR	<0.852	1.036 to 1.039	3.7 to 5.2	300 to 450	Maximum Weight Loss 425–600 °C
Carbon + Silicon Carbide/NBR	—	0.52–1.61	85–125	0.4–0.47	474 °C
Fumed Silica-Nanoclay-EG/ HNBR	0.063/ 0.047/ 0.067	—	—	—	—
6 phr Kevlar Fiber/NBR	0.137	—	15.4	666.6	—
5% SCF/NBR	0.06	0.08	4.75	22	6.15% Loss at 300 °C; 68.83% at 900 °C
Silicon Dioxide/NBR	—	—	—	—	—

Note: MMT = montmorillonite, NBR = nitrile rubber, EG = expanded graphite, SCF = short carbon fiber.

Much of the basic materials work on this topic was performed during the initial period of the Space Age (e.g., Johnson et al. [55]).

Refractory metals are the most commonly used material for nozzles and include niobium, molybdenum, tantalum, tungsten, and rhenium. They are characterized by having very high melting temperatures, retaining their mechanical performance at high temperatures (both advantages), and having very high densities (a noted disadvantage). Tungsten has the highest melting temperature of any metal. Properties of these metals are shown in Table 2-6.

Tungsten and rhenium offer flight-proven performance in the aggressive thermal and chemical environments of solid rocket nozzles. Rhenium is noted as the only ductile material to provide no erosion when highly aluminized SRM propellant is used. The means are available to drive weight down and still utilize refractories. Tungsten can be used to coat lighter materials, such as graphite or carbon-carbon and enable a lighter weight product. Tungsten foam that can also be used as bodies of nozzles has been developed (see Figure 2-9). Next-generation rockets will continue to drive propellant flame temperatures higher, likely past the melting point of tungsten. For these, ceramics will be required, including fiber-reinforced ceramic throats, ceramic-coated carbon-carbon throats, and hybrids of these. Ceramic composites and coatings can also be used to protect against nozzle erosion from exhaust.

Applications of refractory carbides and nitrides are found extensively in machinery and equipment for protection against wear, erosion, and chemical attack. Both bulk materials and coatings are used. The most important bulk material is tungsten carbide sintered with a metallic binder that is usually cobalt.

Regeneratively Cooled Nozzles

In the context of nozzle design, regenerative cooling is a configuration in which some or all of the propellant is passed through tubes or channels or in a jacket around the combustion chamber or nozzle to cool the engine. This is effective because the propellants are often cryogenic. The heated propellant is then fed into a special gas generator or injected directly into the main combustion chamber.

With regenerative cooling, the pressure in the cooling channels is greater than the chamber pressure. The inner liner is therefore under compression, whereas the outer wall of the engine is under significant hoop stresses. The metal of the inner liner is greatly weakened by the high temperature and also undergoes significant thermal expansion at the inner surface while the cold sidewall of the liner constrains the expansion. This sets up significant thermal stresses that can cause the inner surface to crack or craze after multiple firings, particularly at the throat. In addition, the thin inner liner requires mechanical support to withstand the compressive loading

Table 2-6. Refractory Metals and Their Relevant Properties

Name	Niobium	Molybdenum	Tantalum	Tungsten	Rhenium
Melting Point (°C)	2,477	2,622	3,017	3,422	3,186
Boiling Point (°C)	4,743	4,638	5,458	5,930	5,596
Density (g/cm^3)	8.57	10.28	16.69	19.25	21.02
Young's Modulus (GPa)	105	329	186	411	463
Vickers Hardness (MPa)	1,320	1,530	873	3,430	2,450

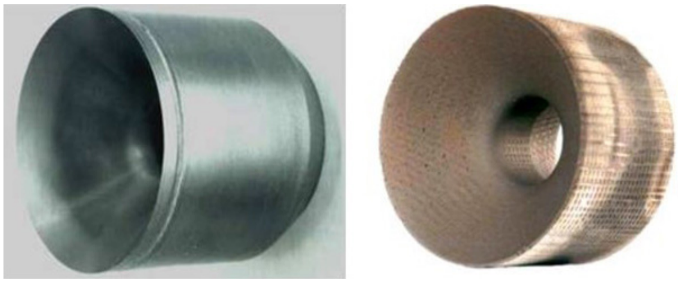


Figure 2-9. A Tungsten-Lined Nozzle Throat Over a Tungsten Foam (Left) and a Ceramic-Lined Nozzle Throat (Right) Used for Space Propulsion *(Source: Ultramet [56])*.

due to the propellant's pressure; this support is usually provided by the sidewalls of the cooling channels and the backing plate. The inner liner is usually constructed of relatively high-temperature, high-thermal-conductivity materials. Traditionally, copper- or nickel-based alloys have been used.

Several different manufacturing techniques can be used to create the complex geometry necessary for regenerative cooling. These include a corrugated metal sheet brazed between the inner and outer liner, hundreds of pipes brazed into the correct shape, or an inner liner with milled cooling channels and an outer liner around that. The geometry can also be created through direct metal 3D printing, as seen on some newer designs such as the SpaceX SuperDraco rocket engine. Blakely-Milner et al. [57] provided an extensive discussion of the use of metal AM in aerospace (which includes nozzles and a number of other propulsion components).

2.1.2.8 Air-Liquid Engines

The main materials issues for LACEs are associated with the mass for the additional components needed to accommodate the compression system, heat exchanger, and TPS. The compressor and heat exchanger running LH_2 must be made of materials that can appropriately handle this material safely for as long as the spacecraft needs to cruise in the lower atmosphere in an oxygen collection phase. Both of these technologies are fairly mature but can likely see improvements from AM to reduce excess mass and optimize geometries (improve the heat transfer to the compressed air), and materials science efforts are attempting to produce high-entropy alloys (those with four, five, or more elements mixed together in roughly equal ratios) that may prove lightweight with superior mechanical/thermal properties.

Research into TPSs is being pushed by the large amount of funding directed toward the development of hypersonic missile systems in response to deployments from China and Russia. Low-Mach (M <10) number engines can operate using actively cooled metallic skins for a TPS (via superalloy materials). However, superalloy materials have a particularly high mass density, and the addition of the requirement of an active cooling system only adds more mass that previously did not exist. For high-Mach (M >10) number engines, the only solution available is a carbon-carbon TPS system with ceramic coatings to protect against oxidization. Research into the development of carbon-carbon along with manufacturing it in product forms of interest and to appropriate quality standards is a high-funded area by the U.S. Department of Defense (DoD). As of the writing of this report, much of the work is sensitive or has now become classified. A previous state-of-the-art report [58] covered this topic in depth in 2020, and an update to this report to address current advances is in development.

2.1.2.9 Future Technology Use

Moving forward, rocket technology offers the most cost-effective and tried-and-true means to lift material off the surface of the Earth and into space.

Solid and Liquid Rockets

Rocket motors offer the power to achieve escape velocities from a wide range of planetary and subplanetary bodies with proven and reliable techniques that have been in place more than 80 years. These systems will continue to be used in the short- and midterm until a more suitable technology is found that can act as a long-term replacement.

Monopropellants

Green monopropellants are a very robust field of research and will continue into the future. Modeling and testing will be needed to confirm that these systems can be used with existing spacecraft designs (as applicable) so that they are properly deployed in upcoming spacecraft in ways that offer the best chance for success and minimize risk. This will likely accelerate due to a potential ban on hydrazine being discussed across the European Union (research of which can be leveraged for U.S. interests).

However, Schmidt and Wucherer stated, "Hydrazine and its methyl derivatives will continue to be used as monopropellants and bipropellant fuels, and materials compatibility data will be needed by launch vehicle and spacecraft designers" [59]. Hydrazine is a proven technology and will continue to be widely used, even as research and exploratory deployment of "green" propellants continue.

Nonreactive Propellants

This technology is likely to continue to be extensively used as the number of smaller satellites continues to increase in the coming years and constellations of cube- and nanosatellites become more prevalent.

Air-Liquid Engines

This technology will be able to significantly leverage and borrow from the large amounts of hypersonic systems development that is taking place across the different branches of the DoD in response to near-peer countries developing these systems. Depending on mission requirements, this may provide a new means to more efficiently launch payloads in the short to midterm.

2.2 ELECTRIC PROPULSION TECHNOLOGIES

Electric propulsion is a type of spacecraft propulsion technique using electrostatic or EM fields to accelerate masses to high speed and generate thrust to produce a change in a spacecraft velocity.

2.2.1 Technology Development/Descriptions

Electric propulsion technologies generate thrust via electrical energy that may be derived either from a solar source, such as photovoltaic arrays, which convert solar radiation to electrical power, or from a nuclear source, such as a space-based fission drive, which splits atomic nuclei to release large amounts of heat energy that is converted to electrical energy. This energy is used to accelerate an onboard propellant by one of three processes:

1. Electrostatic: the production of static electricity
2. EM: the production of magnetism via electricity
3. Electrothermal: the production of heat via electricity (resistojets and arcjets)

Electric propulsion (often referred to in its most commonly employed state as ion engines and excluding thermo-electric space propulsion, such as resistojets and arcjets) takes several forms, but the common thread is the ionization of a neutral propellant (which can start as a solid, liquid, or gas, depending on the type) by extracting electrons to create a cloud of positive ions. This report combines electrostatic and EM propulsion into the electric propulsion group.

The liberated ions are accelerated by the Coulomb force along the direction of the electric field (E-field). The temporarily stored electrons need to be reinjected (by a neutralizer) into the propulsive ions that have been exhausted after the thrust has been extracted, causing the ionized gas to become neutral again. In this way, the exhaust can freely disperse into space without any further electrical interaction with the spacecraft (changing the net charge on the spacecraft, which can cause failures of electronics in the spacecraft and issues with nearby spacecraft if there is a formation).

Electric propulsion schemes typically consume <10 kW of electrical power, have exhaust velocities between 20–50 km/s (corresponding to a specific impulse of 2000–5000 s), and produce thrusts of 25–250 mN with a propulsive efficiency ranging from 65–80%. The largest ion engines examined to date have achieved 100 kW of power and a thrust of 5 N.

With the exceptions of resistojets and arcjets, electric propulsion is practical for use only in a vacuum, as it cannot function if there are other particles present outside the engine. In addition, the small thrust produced is insufficient to overcome any significant atmospheric wind resistance and is insufficient to produce liftoff from any celestial body with any significant surface gravity. However, applications that are appropriate for the successful deployment of electric propulsion include control of the orientation and position of orbiting satellites (some satellites have dozens of low-power ion thrusters) and the use as a main propulsion engine for low-mass robotic space vehicles that can accelerate for a long time to leverage the constant thrust from the engine (such as NASA's Deep Space 1 and Dawn spacecraft).

2.2.1.1 Electrothermal Propulsion

Electrothermal propulsion is a type of hybrid propellant-based propulsion and electric propulsion. In these types of propulsion, propellants are used with an electric-current source to enhance their capabilities.

Resistojet Engine

A resistojet is a type of spacecraft propulsion that combines a cold-gas thruster with basic electric propulsion to produce thrust by heating a typically nonreactive fluid. Heating is usually achieved by ohmic heating (such as a hot incandescent filament). The propellant is heated from the resistor and the hot gas is expelled through a conventional nozzle, as shown in Figure 2-10 [60].

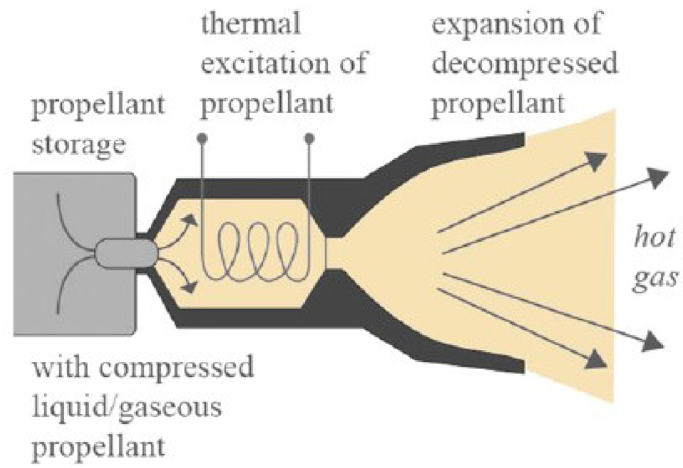


Figure 2-10. Basic Diagram of a Resistojet Engine *(Source: Holste et al. [60])*.

Resistojets can also be considered an evolution of traditional cold-gas thrusters, which are the simplest form of rocket engine available. Their fuel tank holds the propellant, which is then led into the nozzle where it decompresses, providing a reaction force. The heat from the resistor into the propellant gas causes it to expand with more force and results in a higher specific impulse per unit mass of propellant. The degree of thrust from a resistojet engine can be regulated by altering the amount of power applied to the resistor. As a notional example, heating a fluid by 300 °C can result in as much as a 41% increase in the propellant-specific impulse. If a fluid is heated by 900 °C, the corresponding specific impulse can be doubled compared to using an unheated propellant.

Resistojets are designed to bridge the gap between cold-gas thrusters and monopropellants, offering the safety of an inert propellant coupled with a propellant-specific impulse closer to that of hydrazine. The main disadvantage of a resistojet design in comparison to simpler cold-gas thrusters is the need for a power supply (which has mass and volume requirements and may be prohibitive for smaller satellites, such as CubeSats). In addition, the increased technical complexity of a resistojet relative to simpler solutions results in a greater risk of failures. Also, since resistojets do not use chemical combustion, this engine type has a thrust that is orders of magnitude lower than conventional solid-fuel and liquid-propellant rockets, resulting in resistojets being unsuitable for high Δv operations over shorter periods.

Resistojets have been flown in space since 1965, on board United States military Vela satellites. However, they only began to be used in commercial applications in 1980, with the launch of the first satellites in the INTELSAT-V Program. Many geosynchronous-orbit (GEO) spacecraft, and all 95 Iridium satellites, used Aerojet MR-501/MR-502 series resistojet engines. Presently, resistojet propulsion is used for orbit insertion, attitude control, and deorbit of low Earth orbit (LEO) satellites and does well in situations where energy is much more plentiful than mass and where propulsion efficiency needs to be reasonably high but low thrust is acceptable, such as for small satellites and CubeSats.

Arcjet Engines

An arcjet is similar to a resistojet-type spacecraft propulsion. However, in an arcjet, the resistive heating is replaced with an electrical discharge (arc) in the flow of the propellant (often ammonia or hydrazine [see Figure 2-11]). As with resistojet heating, additional energy is imparted into the propellant via this process so that more thermodynamic work can be extracted from a unit mass of propellant. This is done at the cost of increased power consumption and (usually) higher cost. As with resistojet engines, the levels of thrust available from this technology are low compared to that available from chemical rocket engines. Arcjet engines are well suited to station keeping for orbital spacecraft and can replace or augment monopropellant propulsion. They are characterized by having an operational period of months, significantly higher specific impulse than resistojets, and high thrust but low efficiency.

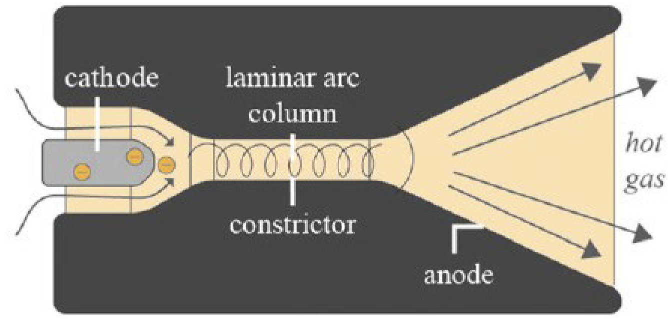


Figure 2-11. Basic Diagram of an Arcjet Engine *(Source: Holste et al. [60])*.

Aerojet MR-510 series arcjet engines are currently used on Lockheed Martin A2100 communications satellites using hydrazine as a propellant, providing over an average specific impulse of 585 s for an input power of 2 kW (see Figure 2-12).

Figure 2-12. MR-510 Arcjet Thrusters From Aerojet Rocketdyne (Designed for Small Satellites With a Low Mass, <2 kg, and an Average Power Consumption of 2 kW) *(Source: Zube et al. [61])*.

In Germany, researchers at the University of Stuttgart's Institute of Space Aviation Systems have been looking into these challenges for years and have developed various hydrogen-powered arcjet engines capable of power outputs from 1–100 kW. The heated hydrogen reaches exit speeds of 16 km/s (9.9 mi/s). One proposed arcjet-propelled test satellite (Baden-Württemberg 1, BW1) was scheduled to launch to the moon by 2010, but it did not. BW-1 would have used polytetrafluoroethylene (PTFE) propellant.

2.2.1.2 Gridded Electrostatic Ion Thrusters

Development of gridded electrostatic ion thrusters began in the 1960s. This technology has been used for both commercial satellite propulsion and scientific missions. These engines use a propellant ionization process that is physically separated from the ion acceleration process (see Figure 2-13).

Propellant ionization takes place in a discharge chamber. The propellant is bombarded by energetic electrons. The energy transferred serves to eject valence electrons from the propellant gas atoms. The positively charged ions are extracted by a system consisting of two or three multi-aperture grids. After entering the grid system near the plasma sheath, the ions are accelerated by the voltage between the grids (screen and accelerator grids) to a final ion energy on the order of 1–2 keV, generating a thrust.

At this point, the engine is emitting a beam of positively charged ions. To keep the spacecraft from accumulating a net charge, a cathode (neutralizer) must be placed near the engine to emit electrons into the ion beam, leaving the propellant exiting into space electrically neutral. This step prevents the exiting beam of ions from being attracted to (and returning) to the spacecraft, negating any engine thrust.

Two examples of space missions are specifically mentioned in the literature that utilize this kind of propulsion scheme.

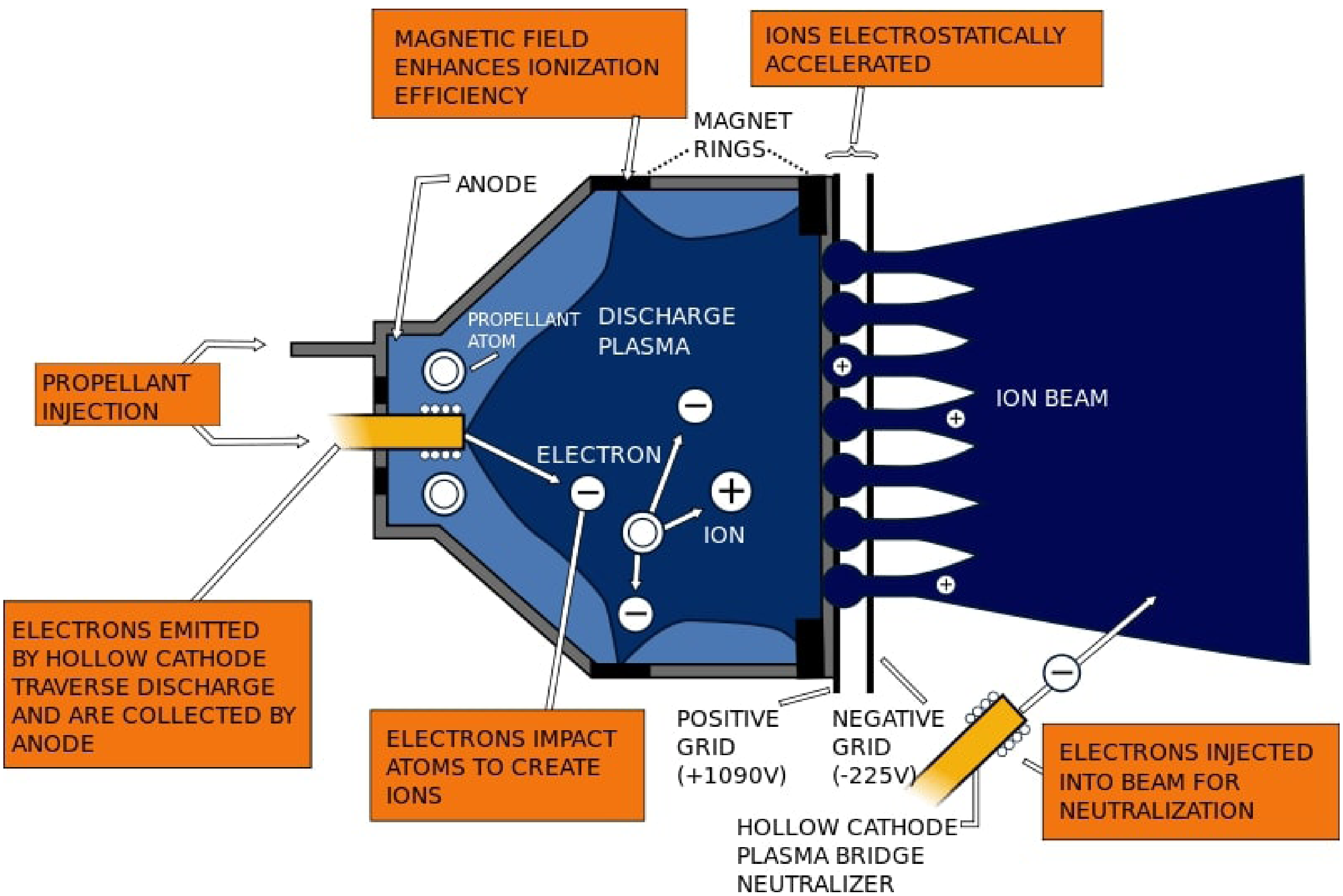


Figure 2-13. Diagram of a Gridded Ion Engine *(Source: Wikimedia Foundation, Inc., [62])*.

1. NASA's Deep Space 1 (last contacted in 2001, it was powered by a xenon fuel source) changed its velocity by 4.3 km/s using <74 kg of fuel and an ion engine for main propulsion.
2. The Dawn spacecraft (last contacted in 2018, again using a xenon fuel source) changed its velocity by 11.5 km/s and was noted as the first NASA mission that was able to orbit and then break orbit from multiple targets (due to the ion engine thrust—previously, this capability was only available using chemical propulsion).

Both spacecraft utilized ion engines as the main propulsion mechanism. Images of each spacecraft are shown in Figure 2-14.

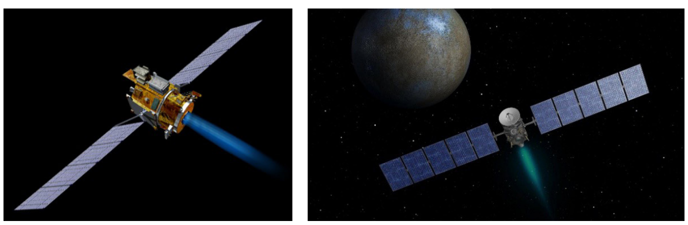


Figure 2-14. The Deep Space 1 (Left) and Dawn (Right) Spacecraft (Operated by NASA) *(Source: NASA [63] [Left], [64] [Right])*.

2.2.1.3 Hall-Effect Thrusters

A Hall thruster uses an applied voltage to accelerate ions to high-exhaust velocities. In a Hall thruster, an attractive negative charge is provided by an electron plasma at the open end of the thruster (rather than a grid). A radial magnetic field (B-field) is used to confine the electrons where the combination of the radial B-field and axial E-field causes the electrons to drift in forming the Hall current. The central spike forms one pole of an electromagnet and is surrounded by an annular space. The other pole of the electromagnet contains a radial B-field.

The propellant, most commonly xenon gas, is fed through the anode, which has numerous small holes in it to act as a gas distributor. As the neutral xenon atoms diffuse into the channel of the thruster, they are ionized by collisions with circulating high-energy electrons. The xenon ions are then accelerated by the E-field between the anode and cathode. Upon exhausting, the ions pull an equal number of electrons with them, creating a plasma plume with no net charge.

The majority of electrons become stuck orbiting in the high radial B-field near the thruster exit plane, trapped in the axial E-fields and radial B-fields. This orbital rotation of the electrons is a circulating Hall current (the source of the Hall thruster). Collisions with other particles and walls, as well as plasma instabilities, allow some electrons to be freed from the B-field and drift toward the anode.

About 20–30% of the discharge current is an electron current, which does not produce thrust, limiting the energetic efficiency of the thruster. The other 70–80% of the current is in the ions. Because most electrons are trapped in the Hall current, they have a long residence time inside the thruster and are able to ionize almost all of the xenon propellant. Modern Hall thrusters have achieved efficiencies as high as 75% through advanced designs.

Another advantage is that these thrusters can use a wider variety of propellants supplied to the anode, (such as krypton and even oxygen), although something easily ionized is needed at the cathode.

Hall thrusters have been flying in space since 1971 (on the Soviet Meteor satellite). Over 240 thrusters have flown in space since then and are routinely flown on commercial LEO and GEO communications satellites, where they are used for orbital insertion and station-keeping.

China's Tiangong space station is fitted with Hall-effect thrusters. The Tianhe core module contains four of these used to adjust and maintain the station's orbit. The development of the Hall-effect thrusters is considered a sensitive topic in China. According to the Chinese Academy of Sciences, the ion drive used on Tiangong has burned continuously for 8,240 hours without issue, indicating their suitability for the Chinese space station's designated 15-year lifespan.

NASA's first Hall thrusters on a human-rated mission will be a combination of 6-kW Hall thrusters provided by Busek and NASA Advanced electric propulsion system Hall thrusters. They will serve as the primary propulsion on Maxar's Power and Propulsion Element for the Lunar Gateway for the Artemis Program (see Figure 2-15).

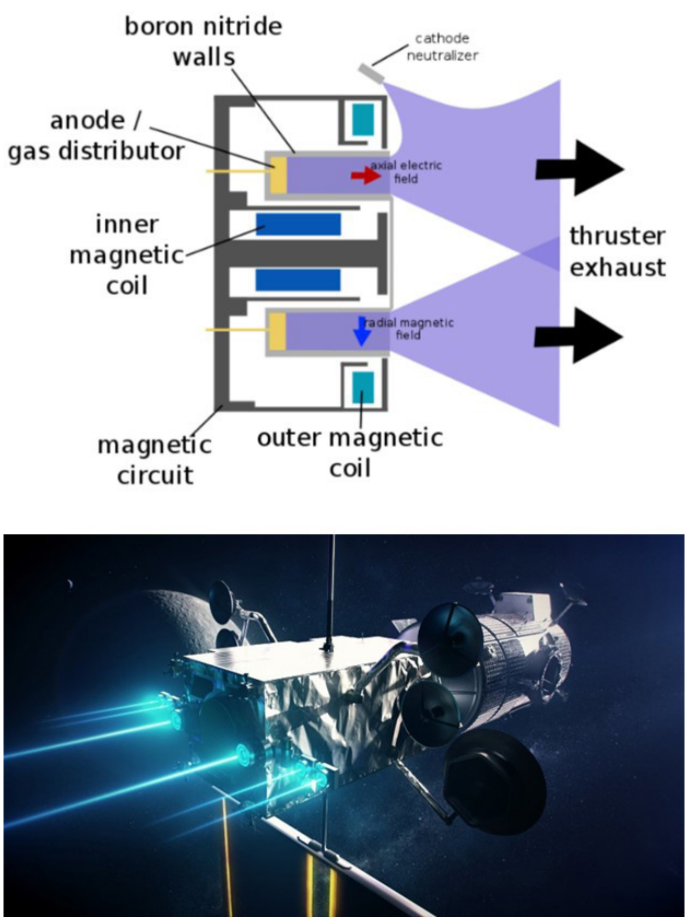


Figure 2-15. Diagram of a Hall-Effect Thruster (Top) and Concept Art From Maxar's Power and Propulsion Element for the Lunar Gateway (Bottom) *(Source: Wikimedia Foundation, Inc., [65] [Top] and NASA [66] [Bottom])*.

2.2.1.4 Field-Emission Electric Propulsion (FEEP)

FEEP thrusters utilize a different fuel type, a room-temperature liquid-metal propellant (such as indium, cerium, or mercury). The design for this propulsion scheme includes a small propellant reservoir to store the liquid metal—a narrow tube or a system of parallel plates the liquid metal flows through, and an accelerator (in this case, a ring or an elongated aperture in a metallic plate). Cerium and indium are often used due to their high atomic masses, low ionization potentials, and low melting points. Once the liquid metal reaches the end of the tube, an E-field is applied between the emitter and the accelerator, causing the liquid surface to deform into a series of protruding cusps, or Taylor cones. At a sufficiently high applied voltage, positive ions are extracted from the tips of the cones (see Figure 2-16). The E-field created by the emitter and the accelerator accelerates these positive ions. An external source of electrons neutralizes the positively charged ion stream to prevent any net charging of the spacecraft.

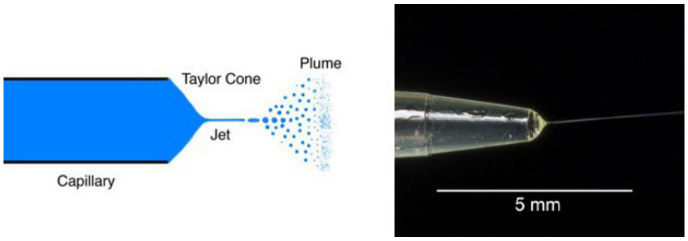


Figure 2-16. Diagram of the Formation of a Taylor Cone From a Capillary (Left) and Example Image of a Meniscus of Polyvinyl Alcohol (a Common 3D-Printing Support Polymer Material) in an Aqueous Solution Showing a Fiber Being Drawn From a Taylor Cone via an Electrospinning Process (Right) *(Source: Wikimedia Foundation, Inc., [67])*.

Due to its very low thrust (on the order of micro- to millinewtons), FEEP thrusters are primarily used for microradian, micronewton attitude control on spacecraft. A modification to this type of thruster (called an electrospray thruster) was used on the ESA/NASA laser interferometer space antenna (LISA) Pathfinder scientific spacecraft (launched in 2016), which is a precursor to the LISA mission (estimated launch of 2037), that will serve as a gravitational-wave observatory. The first FEEP thruster was tested in space in 2018. This thruster, called the indium FEEP multi-emitter (IFM) Nano Thruster, occupies approximately 0.8 U of a CubeSat and can be operated from 10–40 W, resulting in thrust of up to 0.35 mN at I_{sp} between 2,000 and 6,000 s. The first IFM Nano Thruster was successfully integrated into a commercial 3U CubeSat in 2017, after undergoing environmental testing, and was launched in 2018 for a first in-orbit demonstration [68] (see Figure 2-17).

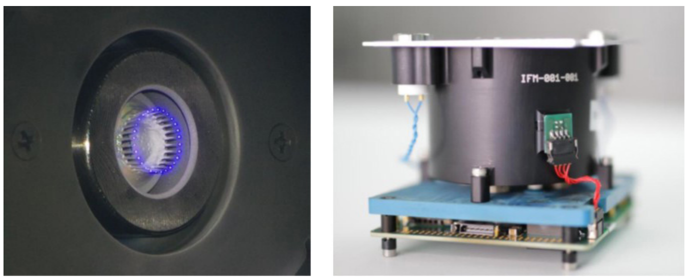


Figure 2-17. IFM Nano Thruster During Ion Emission (Left) and Overall Structure (Right) *(Source: Krejci et al. [68]).*

2.2.1.5 Magnetoplasmadynamic Thrusters

A magnetoplasmadynamic (MPD) thruster uses a Lorentz force to generate thrust. It has been referred to as a Lorentz force accelerator or MPD arcjet. Generally, a gaseous material is ionized and fed into an acceleration chamber, where the B- and E-fields are created using a power source. The particles are propelled by the Lorentz force from the current flowing through the plasma and the B-field (which is either externally applied or induced by the current) and back out through the exhaust chamber. As with other electric propulsion variations, both the engine's specific impulse and thrust increase with power input but the thrust per watt drops.

MPD thrusters have two metal electrodes: (1) a central rod-shaped cathode and (2) a cylindrical anode that surrounds the cathode. Similar to an arc welder, a high-current electric arc is struck between the anode and cathode. As the cathode heats, it emits electrons, which collide with and ionize a propellant gas fuel to create plasma. A B-field is created by the electric current returning to the power supply through the cathode, such as when a corresponding B-field is created when an electrical current travels through a wire. This self-induced B-field interacts with the electric current flowing from the anode to the cathode (through the plasma) to produce a Lorentz force that pushes the plasma out of the engine, creating thrust. An external magnet coil may also be used to provide additional B-fields to help stabilize and accelerate the plasma discharge (applied thrust—self-field-induced thrusters operating at higher power levels do not require this addition). Various propellants such as xenon, neon, argon, hydrogen, hydrazine, and lithium have been examined, with lithium being the option offering the best performance. Diagrams of the thruster are shown in Figure 2-18.

Figure 2-18. Diagrams of an MPD Electric Propulsion Engine *(Source: NASA [69]).*

MPD thrusters have an input power 100–500 kW, exhaust velocities from 15–60 km/s (>100 km/s is possible), a thrust of 2.5–25 N, and an efficiency in the range of 40–60%. They are considered one of the most powerful forms of electric propulsion. An MPD's ability to efficiently convert large amounts of electric power into thrust makes it a candidate for economical delivery of lunar and Martian cargo. MPDs can process more power and create more thrust than any other type of electric propulsion currently available, all while maintaining the high exhaust velocities associated with ion propulsion.

2.2.1.6 Pulsed Plasma Thrusters

Pulsed plasma thrusters (PPTs), or plasma jet engines, are a form of electric propulsion. PPTs are generally considered a simple form of electric propulsion and were flown on two Soviet probes (Zond 2 [used for an attempted flyby of Mars in 1965] and Zond 3 [a successful flyby of the far side of the moon in 1965]). PPTs are an option for spacecraft with a surplus of electrical power.

Most PPTs often use a solid material (normally, PTFE or Teflon) as a propellant gas source. PPT operation involves striking an arc that passes through the fuel, causing ablation and sublimation of the fuel material. The heat generated by the arc causes the resultant gas to turn into a plasma, creating a charged gas cloud. The force of the ablation causes the plasma to be propelled at low speed between charged anode and cathodes. Since the plasma is charged, the fuel allows a current to flow through the plasma, generating an E-field that causes a Lorentz force to accelerate the plasma out of the PPT at a high velocity (similar to a plasma-armature railgun or a capillary discharge—see Figure 2-19).

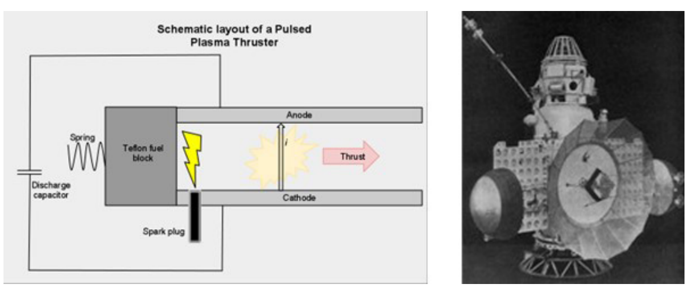


Figure 2-19. Operational Diagram for a PPT (Left) and the Soviet Zond 2 Spacecraft That Operated a PPT (Right) *(Source: Wikimedia Foundation, Inc., [70] [Left], [71] [Right])*.

The engine is operated in a pulsed mode via a capacitor discharge (the pulse frequency is limited by the time needed to recharge the plates following each burst of fuel) at a sufficient frequency to generate almost continuous and smooth thrust. Correspondingly, varying the discharge time allows a tailoring of the thrust. Although the thrust is low, a PPT can operate continuously for extended periods of time, resulting in the ability to achieve a high speed over a long acceleration period.

2.2.2 Electric Propulsion Material Issues and Technology Needs

Here, the materials requirements are broken into two sections. The first section addresses electrothermal engines (resistojets and arcjets). The second section addresses electric propulsion.

2.2.2.1 Electrothermal Propulsion

Materials and technology needs for the future of electrothermal propulsion technologies are discussed next.

Resistojet Engines

The most active area of materials/manufacturing research for resistojets is leveraging AM for propellant reservoirs and nuzzling and piping components, heating elements, optimization of pressure vessel and piping, miniaturization, and propellants.

Coral et al. [72] discuss leveraging AM for producing a resistojet operating on hydrogen propellant. AM allowed the team to produce complex monolithic resistors, resulting in reliable high-efficiency thrusters. The concept was used in combination with advanced cryogenic storage technologies for the development of short-time and high specific-impulse orbital transfers. The simplified two-dimensional thermal design approach adopted is discussed, and its application to the engineering of the resistor is shown for both indium 718 and tungsten. This design produced a thruster that was over 95% efficient.

Similarly, Romei et al. [73] used selective laser sintering (SLS) AM to produce an entire monolithic heat-transfer system (where the ohmic heating is deposited into the propellant), again using AISI 316L stainless steel with an argon gas propellant (see Figure 2-20).

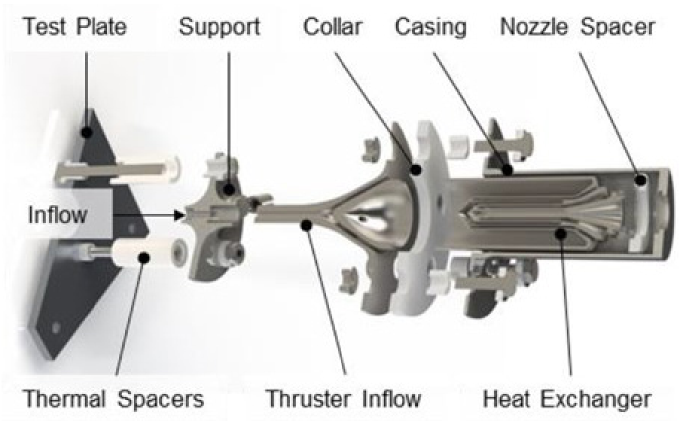


Figure 2-20. SLS AM Heat Exchanger Using AISI 316L for an Argon Propellant *(Source: Romei et al. [73])*.

Kindracki et al. [74] conducted research on the best material for heater elements and determined that for the parameters for an example attitude control system using resistojet thrusters, AISI 316L stainless steel was a good choice.

Resistojet miniaturization can be achieved using microelectromechanical systems (MEMSs). This involves creating very small components, often with micrometer-scale features that are fabricated via silicon chips [75] (see Figure 2-21). MEMSs small size and light weight make them ideal for creating propulsion systems for microspacecraft. Chips can be bonded together, allowing nozzles, heaters, valves, filters, and controls to be sandwiched into very compact units [60]. Research using silicon-based MEMSs for resistojets for attitude control in CubeSats has been demonstrated (see Figure 2-22) [76]. In 2017, researchers at Purdue University extended this concept to liquid-water propellant heated into steam and expanded out of the resistojet nozzle as a green form of micropropulsion. Similar work is being researched at the Delft Space Institute in the Netherlands [77].

A variation of the MEMS resistojet is the Free Molecular Microresistojet or FMMR [77]. Rather than a simple channel and nozzle, the FMMR uses a single chip that features a grid of long slots surrounded by heaters. Using multiple slots instead of a single nozzle helps prevent clogging, which can be fatal when the nozzle is very small [79]. Gas molecules at a very low pressure impact the heater elements as they exit the slots, gaining energy and thus velocity.

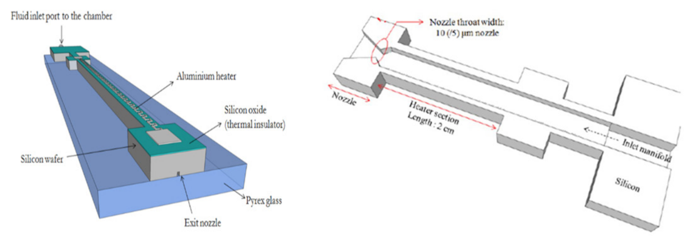


Figure 2-21. Diagrams for a MEMS-Based Resistojet *(Source: Mathew et al. [76])*.

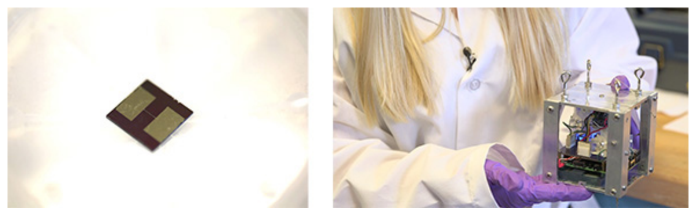


Figure 2-22. MEMS-Based Resistojet for CubeSats Using Steam *(Source: Purdue University [78])*.

Arcjet Engines

Resistojets and arcjets share many similar material issues with one notable difference. Heating in arcjets is produced by an arc to create a plasma to heat the propellant. This means that arcjets require erosion-resistant materials to successfully operate. This area of spacecraft propulsion materials research is well described by O'Reilly et al. [80].

Research into arcjet engines has focused on the usage of different propellants, with erosion reduction to improve lifetime and alternative designs to enable higher thrust forces. The main life-limiting factor for arcjets is ablation of the electrodes and the nozzle throat, in particular, at start up. Recently, experimental work has found that increasing the propellant flow and decreasing the throat diameter decreases the arc root transfer process and improves engine longevity [81].

Propellants used in arcjets include ammonia, hydrazine, or hydrogen. A recent study found argon to be an efficient, low-cost alternative [82], despite the required electrical current being considerably higher than for lower-power arcjets. Although hydrogen has a higher cost, it exhibits higher specific impulses compared to other propellants.

As with many of these technologies, there is significant potential to save mass and increase the efficiency of thermal arcjets via leveraging AM technologies. One example discusses nozzle design using AM of tungsten to produce complex cooling channels [83]. Other options to allow AM of tungsten would likely result in more options for use on future spacecraft. Skalden et al. [83] discuss using these cooling channels for regenerative cooling (feeding the propellant through the channels to cool the nozzle before feeding the heated propellant into the arc discharge chamber). This enables an increase in the thermal efficiency of the arcjet but necessitates the use of low-density propellants such as hydrogen or helium due to their sufficiently high specific heat properties. Arcjets are particularly suited to use in multimode propulsion systems in which more than one propellant is shared among the propellant feed system [84]. Such characteristics may enable arcjet engines to potentially utilize in situ space resources or waste products from chemical rockets, even after depleting the original propellant supply. Such a novel possibility is worth exploring.

2.2.2.2 Electric Propulsion

Electric propulsion has several aeras associated with required materials development: radiation protection/EM shielding, alternative fuels, neutralizers, and erosion protection.

Electronics Protection

If a spacecraft requires a long period to spiral out of its geosynchronous transfer orbit to its target (such as to a lunar target), it will cross multiple times through the Van Allen belts, where it is constantly exposed to hard radiation. This radiation can damage a satellite's electronics, meaning all electrical components must be built radiation hardened and tested accordingly. Similarly, electrical components associated with electric propulsion and the thrusters themselves are both sources and sinks of EM radiation. This radiation can interact with other electronics within the spacecraft. Thus, to best protect a spacecraft from any danger, electric propulsion systems must be tested with respect to their EM compatibility with the rest of the spacecraft (and any other spacecraft that may be interacted with in flight). Since these engines only function under vacuum conditions, special requirements for testing are required to ensure that the measurements comply with existing standards. In addition, outgassing, thermal management, corona discharge, and general manufacturing quality all are frequent challenges that must be addressed.

Alternative Fuels

For the majority of deployed electric propulsion systems, the most commonly used propellant is xenon (a noble gas). However, it is not produced in large quantities. Xenon is produced as a byproduct from liquid air plants, and much of it is dedicated to use as an anesthetic in surgical procedures. As stated by the German Federal Institute for Geosciences and Natural Resources, the annual worldwide production of xenon (in 2017) was about 72 tons (12,200 m^3). This amount will likely be insufficient for future needs, including as a space propulsion fuel, meaning that the price will simultaneously increase and that supply issues will mean the material will be scarce or completely unavailable. As an example, there are currently ~63 plants worldwide with xenon production capacities and ~21 sites capable of performing xenon purification [85]. The mass fraction of xenon in the atmosphere is only 400 parts per billion. If 1,000 tons of air were liquefied, only 400 g of xenon would be produced (assuming a 100% extraction efficiency). The search for readily available, efficient, and cost-effective material alternatives to xenon is therefore driving fundamental research for electric propulsion.

Krypton is often discussed as an alternative to xenon because it is roughly 10 times more abundant in the Earth's atmosphere. However, when using krypton as an electric propulsion fuel, it is necessary to increase the electrical power input (by about 25%) into the krypton fuel required to produce the same thrust for the same amount of krypton vs. xenon. In addition to the increase in power, other factors must be considered before a 1-to-1 substitution is made, including krypton's different ionization energies and excitation and ionization cross sections. Any alternative propellants should be analyzed on a molecular basis for their suitability via various analytical methods. In the case of reactive alternatives, such as iodine, chemical material interactions that do not occur in the case of commonly used xenon must be addressed.

In addition, argon is a commonly used fuel in electric propulsion systems, as it is more widely available. However, argon experiences low thrust performance due to its higher ionization energy and lighter molecular mass, which causes a large amount of input electric power to go into ionization rather than thrust power. Argon is therefore rapidly exhausted from the ionization channel because of its higher thermal velocity [86]. Thus, it is suggested to enhance argon ionization using small amounts of xenon to overcome these problems and increase the mass utilization efficiency of the mixed gas [86]. Argon is presently being used as a propellant in a new thruster on SpaceX's Starlink V2 minisatellite.

From the energetic point of view, the available ionization cross section for any alternative propellant plays an important role. Holste et al. [60] discuss the ionization cross sections for a number of materials, both atomic (the standard propellant used for electric propulsion) and molecular (nonstandard). As an example of utilizing molecular (rather than atomic) propellants, adamantane ($C_{10}H_{16}$, also denoted as $[CH]_4[CH2]_6$) has by far the largest cross section of the examples discussed by Holste et al. [60]. The large cross section is due to the overall size of the molecule (a large cross section makes it easier to hit and cause interactions, such as the ionization of a valence electron). However, molecular propellants (those containing more than one atomic species) possess more possible loss mechanisms than atomic propellants, such as dissociation of the molecule into lighter molecular fragments and excitation of molecular-bond vibrations, rather than valence-electron ionization. In addition to the actual size of the cross sections, the candidate propellant's ionization threshold must also be included in any analysis of alternative propellants. Assuming only this, noble gases perform poorly, as the filled valence shell structure of the atoms is very stable.

Atoms with similarities to a noble gas structure, such as the alkali metals or halogens, can be ionized at much lower electron energies than other propellant candidates. However, these materials are chemically reactive, leading to the increased potential for undesired material interactions. In addition to basic atomic physics considerations, technical aspects must be considered. Propellants must be available in gas form to be ionized inside a thruster (for propellants that start as a solid material, this means they must undergo phase changes from solid to liquid to gas). In addition, the efficiency of the evaporation (the boiling temperature of the propellant) plays an important role. Other possible loss mechanisms that should be considered are electronic or molecular excitation processes, electron capture processes, and the density of the material (for spacecraft mass consideration). Even with the mechanisms necessary to transition from solid to liquid to gas, it may still be advantageous to store the propellant in solid form, which makes a pressure tank unnecessary.

Iodine has been considered a viable propellant alternative to xenon for small satellites since no pressure tank is required (the reservoir can now take on any shape, allowing the leveraging of AM) and the storage volume for the same number of propellant atoms is smaller than for xenon. However, as previously discussed, there are material issues due to the reactivity of iodine that must be addressed. This is especially important for satellites to be operated with an iodine propellant for a longer period. Here, the corrosiveness of the iodine cannot be ignored. A cloud of iodine will build up around the satellite over time and remain in contact with satellite external materials, potentially allowing a number of chemical reactions to occur. Examples of materials exposed to iodine over long periods are shown in Figure 2-23. The black-and-white images are samples exposed to iodine for several months at room temperature (top left is before exposure, and bottom right is after exposure). The colored pictures show samples exposed to iodine at ~80 °C for a few days (all after exposure). Here, there are significant changes for aluminum and copper but the influence on the degradation of the holes was less pronounced. Titanium exhibits a strong layer of iodine growth on the surface and is clearly an unfavorable material for use in iodine-powered engines. There are also clear differences among the stainless steels. AISI 304 shows clear signs of corrosion around the drilled holes, whereas AISI 304L was attacked less strongly. In 625 shows significant growth on its surface.

Similarly, iodine may not be compatible with current neutralizer technology, as the thruster and neutralizer should run on the same propellant for economic reasons and volumetric constraints and to keep the dry mass of the system low. All these materials considerations are required when designing/choosing a propellant for a mission requiring electric-based space propulsion.

Development of Low Work Function Materials (Neutralizer-Free Materials)

A neutralizer in electric propulsion provides an electron source equivalent to the positive ion current to prevent a satellite from being electrically charged. Most commonly, this is a hollow cathode, equipped with a material with a low electron work function. For available materials, low work functions (1.6 eV–2.8 eV) and high temperatures are required to ensure sufficient thermionic

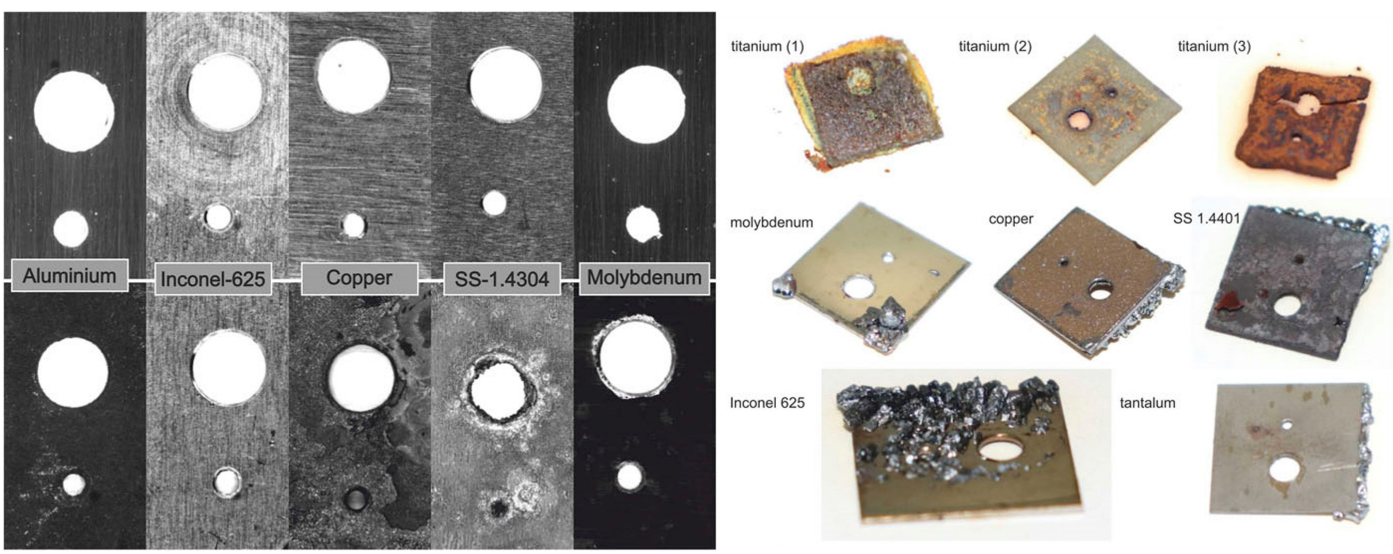


Figure 2-23. Material Samples Exposed to Resublimated Iodine (a Few Grams, Purity >99%) Under Atmospheric Pressure *(Source Holste et al. [60])*.

emission (>1000 °C), which represents a common point of failure due to the thermal loads. The search for novel materials with ever-lower work functions and the development of ion engine's built-in neutralization schemes are constant research topics.

Measurements have yielded work functions for a wide range of materials from a combination of barium oxide and tungsten (BaO-W) and lanthanum hexaboride (LaB_6) for electrode materials provided by Advanced Thermal Devices (ATD) and Fraunhofer IKTS. Further investigations are required to clarify this issue.

Engine-Component Erosion

The physical anode/cathode system (often the grid) is one of the critical components in electrical propulsion and must meet a variety of requirements, such as low material erosion upon ion impact, precisely defined thermal properties, good machinability, and high manufacturing precision [87]. Such properties are required to ensure sufficient component lifetimes (the lifetime of many electric propulsion systems is determined by a combination of available propellant and then the erosion of the grid system). Although difficult to generalize the properties of many different types of Hall-effect thrusters and gridded-ion engines, some numbers are worth mentioning. Typically, the lifetime of a Hall-effect thruster is measured on the order of 10,000 hr [88, 89]. During the same period of time, the erosion phenomena was observed at the radio-ion thruster assembly aboard the ARTEMIS satellite (a GEO communications satellite launched in 2001), which showed a mean increase in the acceleration grid hole diameter of about 25% [90]. By definition, a structural defect in the radio-ion thruster assembly acceleration grid corresponds to an increase in the aperture diameter of 75%. With this in mind, results from a 15,000-hr lifetime test and corresponding extrapolation predict a lifetime for the ARTEMIS in excess of 20,000 hr [91].

Sputtering

As discussed, a major issue in spacecraft electric propulsion is related to the interactions of the neutralized ion plume with parts of the engine itself [87, 92–100], other components of the spacecraft [101–103], or other spacecraft (for constellations) [104] or with parts of the test facility in the case of terrestrial testing [105, 106]. As a result, there is a need to differentiate between damage induced by material sputtering from the ion beam itself and effects from deposition of either the propellant or its sputter products on surfaces of the spacecraft or channel erosion for Hall-effect thrusters [92–97]. External erosion of other components may occur in the case of solar panels [103]. Deposition of material may occur when non-noble gas propellants, such as iodine, indium, and cesium metals, condense on the surfaces of the spacecraft [107].

Sputtering from exposure to ion beams has been widely studied in terms of impinging projectile ions and target materials covering a wide range of projectile energies (eV to MeV) [108]. The physical processes that occur depend on the chemical species involved in the sputtering process and on determining the amount of physical and chemical effects. Physical sputtering takes place solely by momentum transfer from the impinging projectiles to the target atoms and plays a role for all target materials and incident particles with energies above a certain threshold (about 100 eV). Chemical erosion is initiated by chemical reactions between thermalized neutral species from the gas phase with surface atoms. Chemical sputtering occurs when the ion bombardment promotes a chemical reaction between the projectile and target atoms, producing new chemical species that are weakly bound to the surface and easily desorbed into the gas phase [109]. Such chemical processes may play an additional role for chemically reactive propellants such as iodine or when reactive material is sputtered off by impinging ions of the plume and deposited elsewhere.

EM Compatibility

Due to the larger number of electric propulsion systems being used in concurrence with the high density of electronic components on modern spacecraft, aspects of electromagnetic compatibility (EMC) are becoming increasingly important.

All system components of electric propulsion systems, as well as all operational modes, must be taken into account in a comprehensive EMC analysis. For rapid and economic development, it is desirable to fall back on EMC investigations already in early stages of the development of electrical components for electric propulsion systems, since, in later development stages, the availability of testing possibilities decreases. EMC issues, as they concern the EM interactions between satellite system components, are of great relevance for all satellite orbits.

Testing

Currently, most of the new electric propulsion concepts are in a low level of technological maturity. This has consequences, especially for CubeSats and other small satellites, which have very low electrical power reserves and cannot be operated with conventional engines. There is also a need for high-power engines with long lifetimes for larger spacecraft (the Lunar Gateway is one example). This places enormous demands on vacuum facilities for testing and qualification and also on the available peripheral technologies (high-performance power supplies and temperature management mechanisms). In addition, the development of vacuum facilities that can achieve atomic number densities lower than what is seen in existing vacuum chambers is another potential area for improvement.

2.2.3 Electric Propulsion Future Technology Use

Electric propulsion is a necessary technology to allow spacecraft the flexibility to achieve and break orbit and achieve higher velocities. Future uses and material needs are discussed next.

2.2.3.1 Electric Propulsion General Challenges

General thruster materials are subject to the challenges of outgassing, thermal management, emissivity control, manufacturing quality, and challenges with modeling/testing/accepting of novel materials that are needed to enable electric propulsion but are not well characterized or controlled. For instance, in addition to cathodes, electric propulsion systems often require unique magnetic, ceramic, metallic, and/or wire harness materials that have unique and demanding characteristics that must be addressed for successful deployment.

2.2.3.2 Electrothermal Propulsion

Electrothermal propulsion systems will continue to be used for micropropulsion, particularly for CubeSats. Many of the technology subsets are being employed in space for the first time, meaning that there may be several more design iterations before the technology becomes reliable. However, this technology has been used in space for over 50 years and will continue to be used for years to come as AM continues to be leveraged to optimize the technology, novel propellants are tested and further deployed, and lower-power systems are subsequently developed.

2.2.3.3 Electric Propulsion

Electric propulsion systems needs to be produced in large quantities to meet upcoming demand (such as for megaconstellations of satellites). Some of these technology areas have reached a level of maturity on par with their chemical, in-space counterparts (i.e., hydrazine, monopropellants, etc.). L3 xenon-ion propulsion system thrusters have been flying on Boeing satellites for decades. Now, Aerojet/Rocketdyne XR5 Hall thrusters regularly fly on DoD spacecraft. Maxar and Busek Hall thrusters are regularly used in space now as well. SpaceX flies Hall thrusters on all Starlink satellites. These systems now have significant flight heritage, with hundreds flying in space in the 200–5,000-W power range. The future is at the end of this power spectrum. For low-power electric propulsion to be deployed on SmallSats/CubeSats (<100 W), the challenge is how to successfully deploy electric propulsion within a limited mass, volume, and power footprint. For the high powers required for nuclear electric and higher-power solar-electric spacecraft (>10 kW), there are questions as to which electric propulsion technology is best as power increases. It is unclear if this means simply scaling up existing technology or focusing research and development dollars to improve presently low technology-readiness-level (TRL) technologies (or both) is more appropriate. Finally, and perhaps most important, is how to ground test electric propulsion systems in the range of >20 kW, as ground-based vacuum chambers cannot handle the mass flow of the propellant gas.

Despite commercialization and work to date, electric propulsion systems are still the subject of extensive and even fundamental research [110]. The technology offers a wide range of capabilities, from small or very large spacecraft, and will likely continue to be used in greater numbers in the future, both for civilian and DoD spacecraft for Earth, lunar, and interplanetary needs.

2.2.3.4 EMP

PPTs are a flight-proven technology. Future research may need to focus on further development and flight demonstration of self-field and applied-field MPDs and other EM concepts like pulsed-inductive or field-reversed configurations, etc. These types of propulsion systems will become more important as spacecraft become more powerful, as they are more efficient at higher operating powers, and will also be candidates for nuclear electric-propelled spacecraft operating at >100-kW power levels.

2.3 NUCLEAR THERMAL PROPULSION

A nuclear thermal rocket (NTR) is a type of thermal rocket where the heat from a nuclear reaction (often nuclear fission) replaces the chemical energy of the propellants in a chemical rocket. In an NTR, a working fluid, usually LH2, is heated to a high temperature in a nuclear reactor and expands through a nozzle to create thrust. The external nuclear heat source theoretically allows a higher effective exhaust velocity and is expected to double or triple payload capacity compared to chemical propellants that store energy internally. Diagrams of nuclear propulsion technologies compared to a chemical reaction engine are shown in Figure 2-24.

NTRs have been proposed as a spacecraft propulsion technology, with the earliest ground tests occurring in 1955. The United States maintained an NTR development program through 1973, when it was shut down to shift focus to space shuttle development. More than 10 reactors of varying power outputs have been built and tested, but no NTR has flown as of 2021 [111].

2.3.1 Technology Development

A total of 13 research reactors and 6 nuclear engines was built and tested under the Rover/Nuclear Engine for Rocket Vehicle Application (NERVA) programs at the Atomic Energy Commission's Nevada Test Site Nuclear Rocket Development Station (NRDS) and other facilities located across the country [112]. The Rover reactor development and testing efforts were led by the Los Alamos Scientific Laboratory, and the NERVA reactors were designed and built by Westinghouse Electric Corporation (Astronuclear) and Aerojet-General Corporation following a 1961 design competition. The Kiwi (1955–1964), Phoebus (1964–1969), and Peewee (1969–1972) series of reactors were developed and tested under Rover to demonstrate the basics of nuclear rocket technology and to study characteristics of high-temperature nuclear fuels and long-life fuel

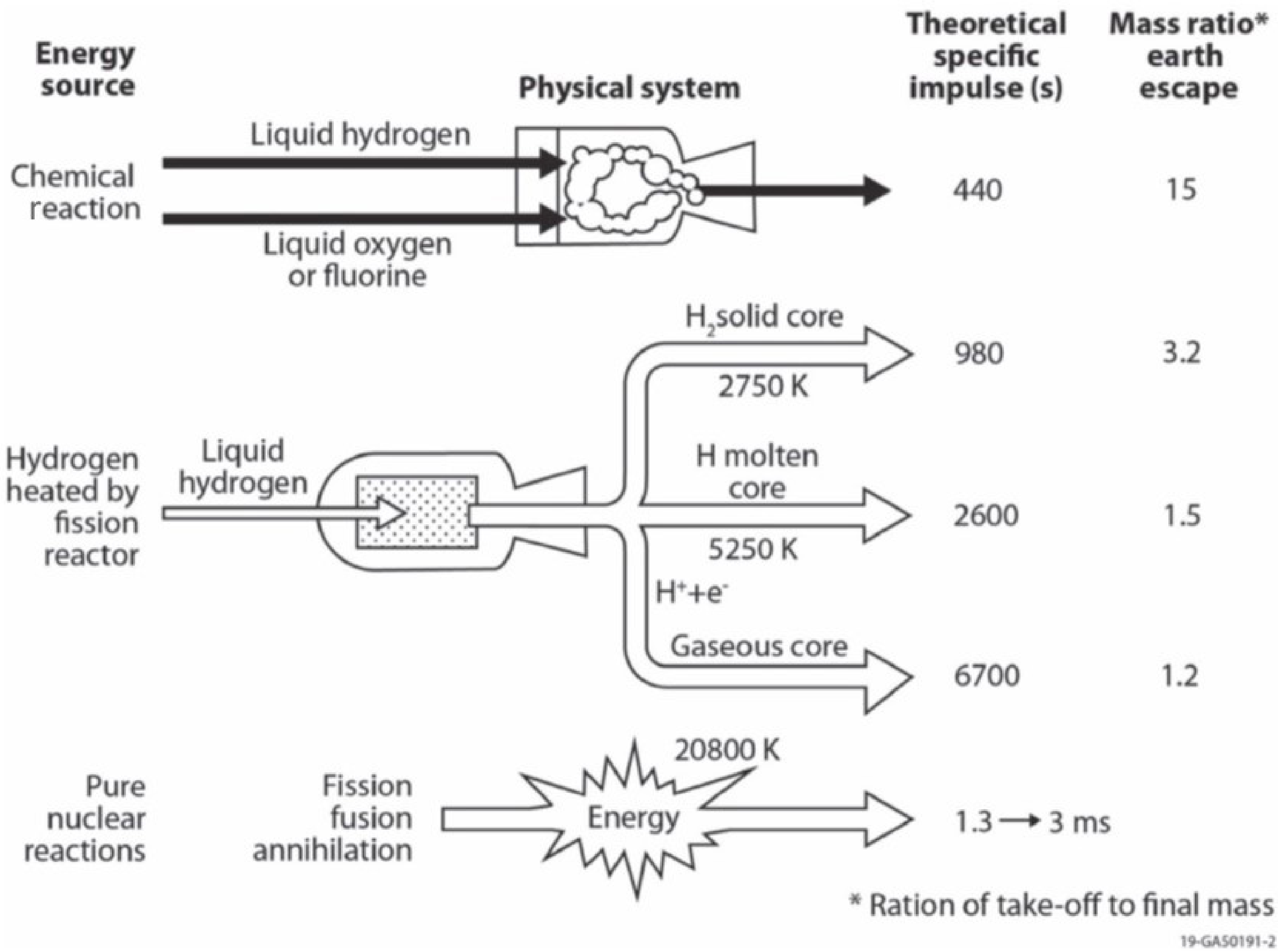


Figure 2-24. Comparison of Rocket Propulsion System Characteristics *(Source: Burns and Johnson [111])*.

elements. The NERVA NRX and XE engines were also built between 1964 and 1969 and tested at NRDS to study the complexities of nuclear engine startup, full-power operation, and shutdown.

Early applications for NTR propulsion used fission processes, but research in the 2010s moved to fusion approaches. The Direct Fusion Drive Project at the Princeton Plasma Physics Laboratory is one such example, although "energy-positive fusion has remained elusive." In 2019, the U.S. Congress approved $125 million in development funding for nuclear thermal propulsion rockets [111].

In May 2022, the Defense Advanced Research Projects Agency (DARPA) issued a request for proposals for the next phase of its Demonstration Rocket for Agile Cislunar Operations (DRACO) Nuclear Thermal Engine Program. This follows on the selection in 2021, of an early engine design by General Atomics and two spacecraft concepts from Blue Origin and Lockheed Martin. The next phases of the program will focus on the design, development, fabrication, and assembly of an NTR engine [113]. A recent press release explicitly states the goal is to test an NTR-enabled spacecraft in Earth orbit during FY27 [114].

2.3.2 Material Issues and Technology Needs

A more detailed diagram of am NTR is shown in Figure 2-25. The primary components that must be addressed are hydrogen propellant tanks, propellant delivery feed system, reactor (and associated subassemblies), and nozzle(s).

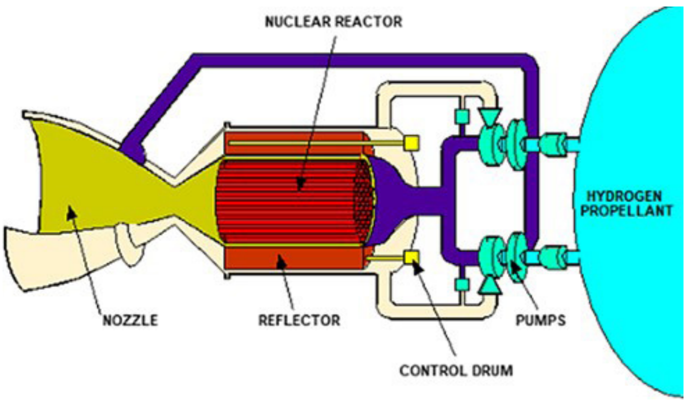


Figure 2-25. A Detailed Expansion of the Diagram for a Nuclear Propulsion System Shown in Figure 2-24 *(Source: NASA [115]).*

The hydrogen propellant tanks store the hydrogen fuel at cryogenic temperatures (~–253 °C) to maintain the propellant in a liquid state via cryogenic fluid management systems.

The propellant delivery feed system includes the plumbing, valves, filters, and fluid management devices to ensure the propellant is adequately delivered to the reactor. The turbopump includes turbomachinery/pumps needed to help push and condition the propellant from the propellant tanks to the reactor.

The reactor includes a number of different subsystems. The first is the fuel assembly. The fuel assembly for current designs contains the flow tubes for the hydrogen, as well as the fuel matrix (uranium-carbide fuels), fuel cladding, and insulators. Uranium-nitride fuel was previously determined to be unstable at the operating temperatures of a nuclear thermal engine (it dissociates into uranium and nitrogen at temperatures at or above 1,800 °C. In addition, all industry and government reactor designs, including the DARPA DRACO, are considering using a carbide-based nuclear fuel concept. Next, the moderator assembly contains elements (such as zirconium hydride or beryllium oxide) to moderate or slow down neutrons to achieve the appropriate neutron energies/velocities for nuclear fission. After this, the control rod/drum assembly is used to maintain the nuclear fission chain reaction. Control rods/drums in the reactor (such as boron carbide) are used as neutron poison (or neutron absorbers) to control or decrease reactivity to maintain criticality and sustain the nuclear fission process. The assembly also allows for rotation of these control drums to adjust the amount of neutron poison on demand. Finally, the reflector is used to minimize neutron leakage. The reflector material (such as beryllium) is placed at the outer radius of the reactor to reflect or scatter neutrons, which would otherwise escape, back into the core. The reflected neutrons can then cause more fissions and improve neutron economy of the reactor. Finally, downstream of the reactor, the hydrogen passes through a nozzle (with converging, throat, and diverging sections) to accelerate the hot exhaust to produce thrust.

Burns and Johnson provide a very good discussion of the materials requirements and concerns for space-based reactor designs [111]. Uranium oxide, uranium nitride, uranium carbide (UC and UC_2), and uranium oxycarbide are ceramic materials that have been studied by various space reactor technology development activities. Each of these materials has advantages and disadvantages related to use in space reactors, but all are capable of achieving the extremely high temperatures that will be needed to operate the engine.

Nuclear thermal propulsion systems can use a range of fluids for thrust and reactor cooling. Examples include hydrogen, ammonia, methane, octane, carbon dioxide, water, and nitrogen [116]. Higher molecular-weight fluids exhibit a lower specific impulse but require less storage capacity and could be mined, or synthesized, on interplanetary trips. Nuclear engine design requires the iterative consideration of reactor neutronic, thermal-hydraulic, and structural characteristics combined with engine system-level performance analysis [117]. Effective design and analysis sequences involve the establishment of a preliminary core design to meet the fundamental neutronic performance requirements of startup criticality and reactor control. Fuel element designs using fixed-fuel compositions and uranium enrichments are developed early in the design process, and then the preliminary design is used to determine neutron and gamma energy deposition characteristics that feed an integrated thermal hydraulic/structural analysis of the core's internal components.

The major problem with the use of graphite and other carbon-based fuels (e.g., uranium carbide [UC and UC_2], uranium-zirconium carbides) in high-temperature space reactor applications is mass-loss produced by a number of interrelated and competing physical processes [118]. These processes include the formation of carbon liquids, loss by vaporization, extensive creep, and corrosion as a result of hydrogen exposure. The most mass loss typically occurred in moderate-temperature regions of the core (<1,700 °C). The amount of hydrogen corrosion that occurs is dependent on reactor operational duration, number of fuel duty cycles, local material temperatures, reactor power density, and compatibility of the fuel and coatings.

There are four major coupled reactions associated with hydrogen corrosion:

1. Exposure to Hydrogen Gas
2. Nonuniform Loading/Cycling of the Fuel
3. Radiation Exposure
4. Creep

The major barrier to demonstrating a high-performance nuclear propulsion system is developing a fuel that can survive the extreme operating conditions that will be required during space flight missions. The fuel operational characteristics that need to be satisfied during reactor operations include:

1. Minimizing High-Temperature Hydrogen Corrosion
2. Minimizing Brittle Fracture Behavior at Low Temperatures
3. Minimizing Fuel Creep and Vaporization at High Temperatures
4. Minimizing Radiation Damage That Impairs Fuel Performance
5. Managing High Transient Thermal and Mechanical Stresses on the Fuel During Reactor Startup
6. Rapid Heat Transferring From the Fuel to the Propellant
7. Matching Thermal Expansion Coefficients for the Different Materials Used in the Fuel to Avoid Fuel Constituent Separation During Reactor Operation
8. High Uranium Loading to Allow for use of Low Enriched-Uranium Fuel
9. Using Low Fuel and Reactor System Masses to Minimize Launch Costs
10. Limiting Fuel Dissociation and Constituent Migration During Reactor Operation
11. Limiting Cracking of Fuel and Coatings to Minimize Hydrogen Ingress Into the Fuel During Reactor Operations

2.3.3 Future Technology Use

NASA is again exploring the feasibility of building and operating nuclear fission systems for deep space science and exploration missions. The primary objective for feasibility studies is to identify systems that can be used to support human missions to Mars.

Regardless of the materials selection, it is likely that whatever fuel is selected will have to operate close to its thermal and mechanical failure limits. There will be little margin for error in system operation, so a significant amount of research and testing will be needed before a safe and reliable system can be built and operated. The majority of future work associated with developing space reactor propulsion and power-generation reactors will be associated with designing, building, and operating the equipment and experiments that will build on past testing programs and lead to fuel and reactor qualification and public acceptance. This technology is not mature for near- or midterm missions, but there may be possibilities for deployment in the longer term (20+ years).

2.4 PROPELLANTLESS PROPULSION TECHNIQUES

There are a number of other propulsion technologies that do not fall into the previous categories. Those are discussed in this section.

2.4.1 Technology Development/Descriptions

Present, relevant propellantless technology includes three categories that have been demonstrated to have feasibility for future use in some way, shape, or form. These include (1) mass drivers, (2) solar sails, and (3) space tethers.

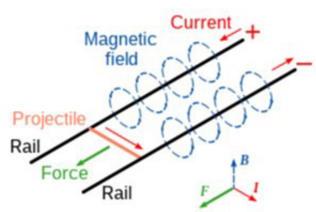
2.4.1.1 Mass Drivers

Practical mass drivers often come in two different options: (1) a means to launch an object from a larger body (such as the Earth or the moon) or (2) a means of ejecting a small mass to maneuver a spacecraft through the transfer of momentum from the ejected object. These objectives are achieved most commonly using EM railguns or coilguns. With these technologies, there is a certain amount of control over the projectile velocity (both in its acceleration profile and in its final projectile velocity) by varying the amount of applied B-field. Another advantage to this type of propulsion is the high speed the projectile can achieve in a short launch distance.

Railguns

Railguns have been researched as weapons because of the increase in the kinetic energy carried in a projectile. Projectiles from propellant-driven guns have difficultly achieving muzzle velocities in excess of ~1.6 km/s and cannot readily achieve muzzle velocities of more than ~2 km/s. Solid-armature railguns launch projectiles that can exceed 3 km/s, and plasma-armature railguns can theoretically exceed this value by as much as a factor of 10.

A railgun is often designed for use as a terrestrial weapon but can be used in a nonweaponized propulsion mechanism configuration. A railgun uses an applied current to develop an EM force to launch projectiles to a high velocity via a pair of parallel conductors (rails). A sliding armature is accelerated by the EM effects of a current that flows down one rail, into the armature, and then back along the other rail (see Figure 2-26). The high current and shape of the bore create a propulsive force to launch the projectile (satellite or other mass to launch) at a high acceleration.



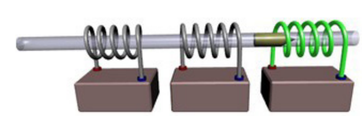


Figure 2-26. Schematic Diagrams of Selected Mass Drivers: Railgun (Left) and Coilgun (Right) *(Source: Wikimedia Foundation, Inc., [119] [Left], [120] [Right])*.

The most practical form of a railgun is a solid-armature (metallic) railgun. Plasma-armature railguns replace the solid, electrically conductive armature joining the rails with an electrically conductive plasma, significantly lowering the energy required to launch a mass (since the extra mass of the armature no longer has to be accelerated with the projectile).

Solid-armature railguns have been extensively tested terrestrially to replace traditional powder guns. Prior to 2010, the U.S. Army funded railgun research for the potential to replace howitzers on heavy tanks. From 2005 until recently (reported in 2021), the U.S. Navy (USN) was funding railgun research to replace traditional cannons used on surface ships (see Figure 2-27). This funding has ceased to permit a transition to the development of hypersonic missiles [121]. China continues development of its internal railgun effort for its Navy (see Figure 2-27) and claims to have a prototype on a ship being tested at sea [122].

Figure 2-27. Examples of Terrestrially Deployed Railguns: USN Railgun Test Setup at the Naval Surface Warfare Cener Dahlgren Division (Left) and People's Liberation Army Navy Sea-Deployed Railgun (Right) *(Source: USN [123] [Right] and Asia Times Staff [124] [Right])*.

The Air Force Office of Scientific Research (AFOSR) funded a multi-university research initiative that explored the technology space available to launch a nanosatellite to space (with a goal of achieving a launch velocity of 7 km/s, enough to place a small project [several grams] with microelectronics into LEO). Such a system was envisioned to be deployed within a large aircraft and launch its projectile at a high altitude to avoid drag associated with the dense, lower atmosphere. The final result from this project was a surrogate projectile being launched to ~5.2 km/s (see Figure 2-28 for end-system graphic and test setup at the Institute for Advanced Technology) [125].

Coilguns

As with railguns, much coilgun research has been weapons based. A coilgun (also known as a Gauss rifle) is a type of mass driver consisting of one or more coils used as electromagnets configured like a linear motor to accelerate a magnetic or electrically conducting projectile (or projectile body) to a high velocity.

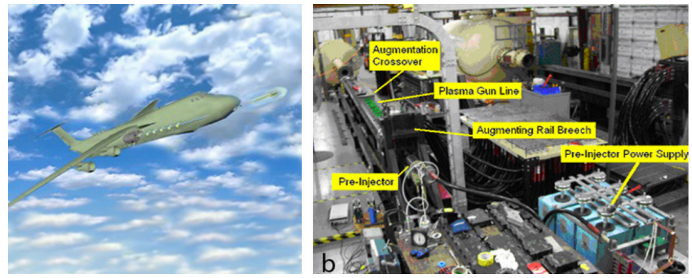


Figure 2-28. Graphic (Left) and Test Setup (Right) of a Plasma-Armature Railgun Proposed and Tested as a Means to Launch Nanosatellites Into Orbit From a High-Altitude Aircraft *(Source: McNab [126] [Left] and McNab et al. [125] [Right])*.

Coilguns generally consist of one or more coils arranged along a barrel, producing a projectile acceleration length along the central axis of the coils. The coils are switched on and off in a precisely timed sequence, resulting in the projectile being accelerated down the barrel via the induced magnetic forces (see Figure 2-26).

Coilguns have previously been considered applicable primarily for low-speed launch, partially because speeds of 1.5 km/s or less have been demonstrated, but also due to concern of the peak power necessary to drive coils at the muzzle of high-speed guns and the precision of switching energy into these coils [127]. Due to these specific precision requirements (switching required to activate/deactivate coil sections properly accelerate a projectile), less experimental research at technological levels of interest has been performed on this technology. DARPA funded an effort to develop both a coilgun and railgun to accelerate a mortar projectile [128]. In addition, a number of theoretical NASA proposals have been put forward to use coilguns to move large amounts of mass between the moon and the Earth [129].

2.4.1.2 Solar Sails

Solar sails (sometimes called light or photonic sails) are a method of spacecraft propulsion using radiation pressure exerted by sunlight on large mirrors (see examples in Figure 2-29). The first dedicated and successful spacecraft to make use of the technology was IKAROS, launched in 2010.

Figure 2-29. Publicity Image of the IKAROS Spacecraft (Left) and Image of the Deployed Sail on the ADEO Braking Sail Used for Deorbiting (Right) *(Source: Wikimedia Foundation, Inc., [130] [Left] and ESA [131] [Right]).*

Solar radiation pressure has been shown to affect all spacecraft, whether in interplanetary space or in orbit around a planet or small body. As an example, a typical spacecraft travelling to Mars will be inadvertently displaced as much as thousands of kilometers from solar pressure acting on the sun facing surfaces of the spacecraft. As a result, these effects must be addressed during trajectory planning. Similarly, solar pressure also affects the orientation of a spacecraft—another factor that must be included in spacecraft design.

Solar sails work similarly to a sailboat powered by wind. The light radiation emitted from the sun exerts a very small but constant force on the sail if it is properly oriented to catch the radiation. In addition, high-energy lasers have been suggested as an alternative source of radiation pressure to exert a much greater force—a concept known as beam sailing (although little experimental work has been done in this area). Solar sail craft offer the possibility of low-cost operations combined with long operating lifetimes, and, as they have few moving parts and use no propellant, they can potentially be used numerous times for delivery of payloads.

As a practical example, the total force exerted on an 800-m × 800-m (0.8-km × 0.8-km) square solar sail is a constant ~5 N (1.1 lbf) at 1 astronomical unit (AU) (or the Earth's distance from the sun). This force is exerted almost constantly and the collective effect over time is great enough to be considered a potential manner of propelling spacecraft.

A limited number of missions have been launched using solar sails as a propulsion mechanism (see Table 2-7). One of the more successful missions was launched by JAXA and called IKAROS in 2010. JAXA scientists stated on 9 July 2010, that the measured thrust force by the solar radiation pressure on IKAROS' 196 m^2 sail is 1.12 mN. The most recent use of a solar sail was on NASA's Near-Earth Asteroid Scout (NEA Scout), although the spacecraft failed prior to deployment. The goal of NEA Scout was to demonstrate using an extremely small spacecraft, propelled by a solar sail, to perform reconnaissance of an asteroid at low cost. In particular, the goal was to develop a capability that would close knowledge gaps about near-Earth asteroids in the 1–100-m size range due to challenges detecting, tracking, and observing these objects for extended periods. The United States Space Force (USSF) has been investigating sails for pole-sitter spacecraft (spacecraft that are stationed along the polar axis of the Earth) for persistent observation capabilities but may use electric propulsion in the near term.

2.4.1.3 Space Tethers

Space tethers come in several different types: electrodynamic, momentum exchange, formation flight, and universal orbital support system tethers.

Electrodynamic Tethers

Electrodynamic tethers are conducting tethers that carry a current that can generate either thrust or drag from a planetary B-field similar to an electric motor. They are long conducting wires that

Table 2-7. Use of Solar Sails as Space Propulsion on Fielded Missions

Mission	Year	Country	Sail Size	Comments
Znamya 2	1993	Russia	20-m maximum dimension	Propulsion not sufficiently demonstrated
Znamya 2.5	1999	Russia	25-m maximum dimension	Failed to deploy
COSMOS 1	2005	Planetary Society	600 m^2	Vehicle failed to reach orbit
IKAROS 2010	2010	Japan	192 m^2	Appears to have demonstrated solar sailing
NanoSail-D2	2011	NASA	10 m^2	Used as deorbiting device
LightSail 1	2015	Planetary Society	32 m^2	Declared a success
LightSail 2	2019	Planetary Society	32 m^2	Increased orbit using sail
NEA Scout	2022	NASA	85 m^2	Spacecraft failed before deployment
ADEO	2022	ESA	0.6 m	Used as a deorbiting device
Solar Cruiser	NA	NASA	1,672 m^2	In development

operate similarly to a generator by converting their kinetic energy to electrical energy, or as motors, converting electrical energy to kinetic energy. Voltage is generated across the conductive tether by its motion through the Earth's B-field. The choice of the metal conductor to be used in an electrodynamic tether is determined by a variety of factors. Primary factors usually include high electrical conductivity and low density. Secondary factors include cost, strength, and melting point.

Momentum Exchange Tethers

Momentum exchange tethers can be either rotating or nonrotating tethers that capture an arriving spacecraft and release it later into a different orbit (with a correspondingly different velocity). Momentum exchange tethers can be used for orbital maneuvering, or as part of a planetary-surface-to-orbit/orbit-to-escape-velocity propulsion. A rotating tether will create a controlled force on the end masses of the system due to centrifugal acceleration. As the tether system rotates, the objects on either end of the tether experience a continuous acceleration, the magnitude of which depends on the length of the tether and the rotation rate. Momentum exchange occurs when an end body is released during the rotation. The transfer of momentum to the released object will cause the rotating tether to lose energy, and thus lose velocity and altitude (possibly resulting in a deorbit). Illustrations are shown in Figure 2-30 [132].

Figure 2-30. Illustrations of Satellites With Tethers *(Source: NASA [132])*.

Tethered Formation Flight

Tethered formation flight typically involves a nonconductive tether that accurately maintains a set distance between multiple space vehicles flying in formation. The Tethered Experiment for Mars Interplanetary Operations (TEMPO) was a proposed 2011 experiment to study the technique.

Universal Orbital Support System

This type of technology, although a type of tether, is still conceptual at this point in time. It is based on suspending an object from a tether orbiting in space (such as might be used for a space elevator or skyhook to achieve propellant-free orbital transfers). This technology is materials limited and not expected to be feasible in the short to midterm without breakthrough type advances. From these technology choices, there have been a number of space tether flights since the 1960s (see Table 2-8).

2.4.2 Propellantless Propulsion Material Issues and Technology Needs

Separate from the other technologies, there are particular materials needs and developments required to give propellantless technologies the best chance at success.

2.4.2.1 Mass Drivers

For each of these technologies, while not utilizing chemical energetics in bore (propellants), energetics are required to accelerate the projectiles (in this case, usually large banks of capacitors capable of producing mega-amps of current in a few milliseconds). Faster launches can be achieved but require longer acceleration lengths. Present capacitor technology would allow ship-based use of a railgun (such as sought by the USN), but when the amount of space available decreases to that on an M-1 Abrams tank (such as to replace a 120-mm conventional powder gun with a railgun), present technology is insufficient. Research in capacitor/battery materials is needed to efficiently deploy this technology and drive down the system sizes.

Railgun Specific

From a materials perspective, the most common conductor materials in a railgun are copper rails (copper is very electrically and thermally conductive) and aluminum armatures (lightweight and reasonably electrically and thermally conductive). In-bore materials issues have been a primary driver in railgun research for years to

Table 2-8. Tethered Space Missions Deployed by Different Entities Since the 1960s

Mission Name	Year	Nation	Space Agency
Gemini 11	1966	USA	NASA
Tethered Satellite System-1 (TSS-1)	1992	USA	NASA
Small Expendable Deployment System-1 (SEDS-1)	1993	USA	NASA
Plasma Motor Generator	1993	USA	NASA
Small Expendable Deployment System-2 (SEDS-2)	1994	USA	NASA
Tethered Satellite System-1R (TSS-1R)	1996	USA	NASA
Tether Physics and Survivability Experiment (TiPS)	1996	USA	NRL
Young Engineers' Satellite (YES)	1997	EU	ESA
Advanced Tether Experiment (ATEx)	1999	USA	NRL
Young Engineers' Satellite 2 (YES2)	2007	EU	ESA
Multi-Application Survivable Tether (MAST)	2007	USA	NASA
Space Tethered Autonomous Robotic Satellite (STARS)	2009	Japan	Private
Space Tethered Autonomous Robotic Satellite-II (STARS-II)	2014	Japan	Private
Kounotori Integrated Tether Experiment (KITE)	2016	Japan	JAXA
Space Tethered Autonomous Robotic Satellite-III (STARS-III)	2016	Japan	Private
Tethered Electrodynamic Propulsion CubeSate Experiment (TEPCE)	2019	USA	NRL
Miniature Tether Electrodynamics Experiment (MiTEE)	2021	USA	NASA
Electrodynamic Tether for Passive Consumable-less Deorbit Kit (E.T.PACK)	2024	EU	ESA

Note: NRL = U.S. Naval Research Laboratory allow the bore components to survive more than one or two launches. The primary in-bore damage mechanisms affecting railguns are hypervelocity gouging, rail erosion, and transition to arcing contact. An ideal material for an armature from this perspective is magnesium or aluminum due to their light weight and high electrical conductivity. However, these materials have low melting temperatures and become very corrosive in the state that results from the high temperatures in bore.

Hypervelocity gouging was first observed in rocket sled motor tests performed in the 1950s and 1960s. Gouging takes the form of teardrop-shaped craters on the rail surface that disrupt rail/armature contact. These usually only occur above a speed threshold that is dependent on the slider (armature) and rail material properties (see Figure 2-31). If gouging occurs, a subsequently fired launch package running over a gouge will destabilize, resulting in launch package failure. Gouging is believed to be the result of instabilities associated with high-speed thermoplastic shear [133]. Different armature/rail material pairs produce different gouging onset speeds. Watt [133] provides a very good overview on the effect of material pairings. For common material configurations (aluminum armature/copper rail), gouging takes place when the armature reaches 1.8 km/s.

Erosion occurs due to the high currents used and the armature locally melting in bore during launch, ejecting molten material onto the rail. The ejected molten armature material, most commonly an aluminum alloy, melts and erodes the rail surface (see Figure 2-31). An eroded surface can no longer maintain good contact with the armature, which leads to transition to arcing contact. Transition to arcing contact occurs when the armature/rail interface degrades from a solid/solid, to a liquid/solid, and finally to a gas/plasma contact. Upon the formation of a plasma contact, the high pressure pushes the armature from the rail and results in projectile and often bore failure.

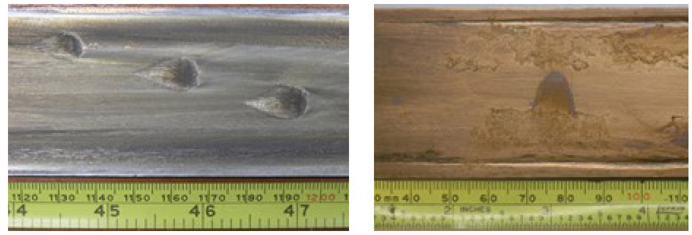


Figure 2-31. Examples of Common Damage in Solid-Armature Railguns: Hypervelocity Gouging (Left) and Rail Erosion (Right) *(Source: Watt and Motes [134] [Left] and Zielinski et al. [135] [Right]).*

For railguns, the ideal material for a rail or armature is a low-density, very high melting temperature, and very electrically conductive/thermal material. In addition, the material pair must be evaluated for the propensity to be susceptible to hypervelocity gouging. The most practical rail material providing the most desirable performance would be a refractory material (such as molybdenum), due to its acceptable conductivity, gouge resistance, and high temperature. However, refractories are very expensive, not readily produced in the form factors needed (long rail shapes), and very dense (heavy). Material coatings, such as with electroplating of aluminum on copper rails, have been found to delay the onset of, but not completely prevent, gouging [134].

Plasma-armature railguns remove the solid armature entirely and allow the projectile to ride an arc of plasma. For this type of propulsion to succeed, the rails must be able to survive the plasma arc and not experience surface melting, which changes the rail surface shape and can destabilize the projectile. In addition, appropriate materials must be used in the back of the launch package to shield the launch package from the effects of the plasma arc (high temperatures).

Coilgun Specific

Coilguns do not require sliding contacts but do need highly conductive materials in the coils to accept the current pulses necessary to accelerate a projectile. Even silver and copper, which are materials with the highest available electrical conductivities, are subjected to very high surface temperatures as a result of the current pulses. In addition, switching technology (such as materials used for high-current, solid-state switches capable of operating reliably around high voltages and currents) needs to be further researched and developed to see it fully implemented.

2.4.2.2 Solar Sails

There are a number of materials issues that need to be addressed for more widescale and successful deployment of solar sails. Largely, these issues increase as distance from Earth increases (outside of the protective B-field) but may impact lunar-based missions.

Davoyan et al. [136] provide a comprehensive review of the materials available and the material issues associated with the use of solar sails. Solar sails employed on space missions up to this point (see Table 2-7) have relied on a consistent sail architecture—thin aluminum films (50–100 nm thick) on the solar-facing side applied to a reinforcing polymer substrate (usually a polyamide such as Kapton, clear polymer 1 [CP1], or Mylar). These can be made very thin (5 µm thick) and allow the mass per unit area to be driven down so that the sail takes up the least weight possible [137].

Thermal Management

Thermal management of solar sails becomes a problem when the sails are taken in close to the sun to accelerate the spacecraft or when using high-power lasers to quickly accelerate a spacecraft. The presently employed sail structure does not allow complete reflectance of the radiation imparted onto it. For the high heat fluxes (and therefore radiation pressures) needed for significant acceleration, even minor absorbance of some radiation into the material will greatly heat the sail. Several outcomes are possible when this occurs. First is complete sail degradation (the aluminum and/or the polymer substructure will melt or evaporate). Second is structural deformation of the sail due to thermal expansion of the aluminum film. In addition to direct heating from the primary irradiance source (the sun or a laser), another source of heating may be the solar wind and energetic particles.

An optimum structure would eliminate radiation absorption and include passive thermal regulation by being exceptionally reflective on the radiation facing surface to ensure maximum transfer of photon momentum for radiation pressure propulsion. This would include a reflectance of 1 for the part of the EM spectrum that the sail is being irradiated with and an emissivity of 1 for the remainder of the spectrum. The substrate (or backside) of the sail can also be engineered to assist in thermal management and reject heat into space, such as by using carbon infill in the polymer matrix to increase the thermal conductivity. Higher-temperature polymers for the backside substrate are also being examined. Newer films are being investigated, but these need to be low-enough density to warrant use and be space qualified.

Another option to address thermal management issues is the use of entirely dielectric sails. Dielectric materials can be made to be low loss and reflective and have a high melting temperature (such as silicon-oxygen tetrahedron, alumina, and titanium dioxide). In this way, the front and backside material mismatches in the sail are decoupled and the entire sail interacts with the imparted radiation. This offers both advantages and disadvantages. Work must be done to tailor materials to ensure a careful balance is maintained between absorptivity and emissivity on different parts of the EM spectrum. In addition to "simple" dielectric sails, metamaterials (metasurfaces), Bragg mirrors, and liquid crystal have been proposed for use. These materials (passive or actively controlled depending on implementation) provide the ability to gain agile control over light reflectance and transmittance (possibly over different parts of the sail), enabling the ability to steer and accept or reject heat from different parts of the sail. Electrically tunable metasurfaces and liquid crystals also provide the ability to manipulate the phase and amplitude of the incoming radiation, providing another means of sail control. Ultralow-power (passive) options include diffraction gratings and metasurfaces. In this way, it may be possible to tune out certain pieces of the EM spectrum, depending on what is required, and manage the heating of the sail. Graphics of these differing requirements are shown in Figures 2-32 and 2-33.

Mechanical Issues

In addition to the thermal issues, mechanical strength must be considered as well. The common structure used for solar sails (aluminum front side/polymer backside) is exceedingly thin and composed of materials with fairly low yield strengths (<100 MPa for polymers). The overall sail structure and shape can be supported with booms and struts, but these add mass that must be accelerated as well. AM and structural optimization can limit mass additions. Ideally, the amount of supporting structure needs to be minimized. In addition, the sail and supporting structure(s) must survive packaging, launch, and deployment. In addition, if high-radiation pressures are employed on the sail material itself (either near the sun or from active lasing), the pressure on the sail may exceed that of the material system, causing tearing. All of these potential occurrences mean that mechanical strength must not be neglected when designing these devices and selecting materials.

Space-Based Damage Mechanisms

The interplanetary medium offers many ways to damage sail materials. Solar plasma can damage the outer layers of the sail material. Radiation damage can occur as well. Development of sail materials resistant to solar plasma, high heat loads, and high-energy radiation is possible by using materials designed for highly corrosive environments, such as high-power ion and Hall thrusters, fusion reactor walls, and coatings of hypersonic vehicles. Refractory and rare Earth metals, refractory ceramics, and carbon are good choices. However, the availability of these materials in thin films and over the large areas required is something that is not currently available.

Davoyan et al. [136] also mention the effects of space damage on micro-architectured materials. Micro-architectured surfaces distribute heat and ion implantation more evenly, reduce implanted ion atom residence time, and reduce thermal stresses (compared to planar smooth surfaces). However, the need for ultrathin (≤1 μm) and low aerial density (≤1 g/m^2) solar sail materials with low sunlight absorbance (ideally ~10%) poses additional constraints. Additionally, in-space

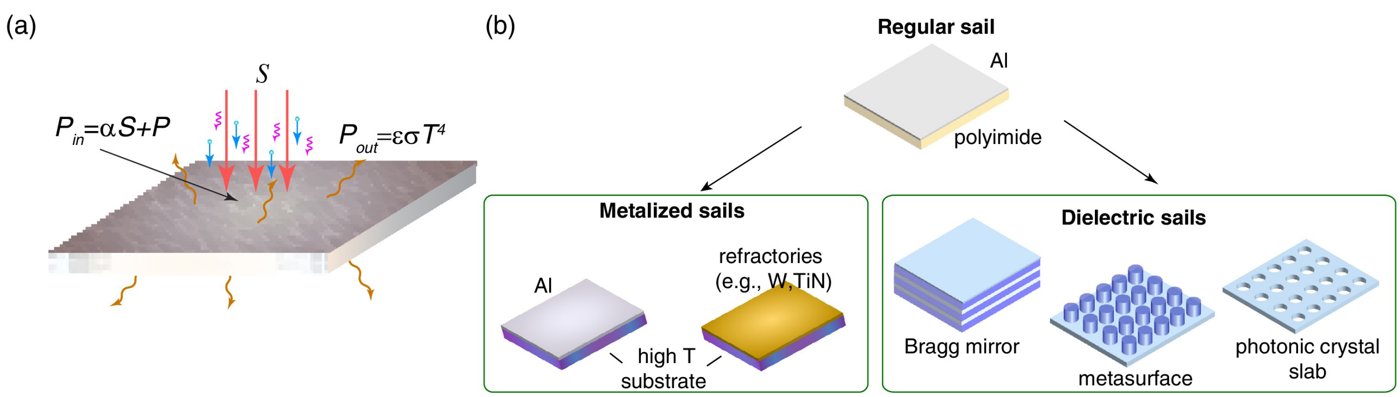


Figure 2-32. Thermal Management and Sail Design: Steady-State-Sail Power Balance (Left) and Schematic Illustrations of Current Sail Design and Potential Nanophotonic Structures, Including Bragg Mirrors, Photonic Crystal Slabs, and Metasurfaces (Right) *(Source: Davoyan et al. [136])*.

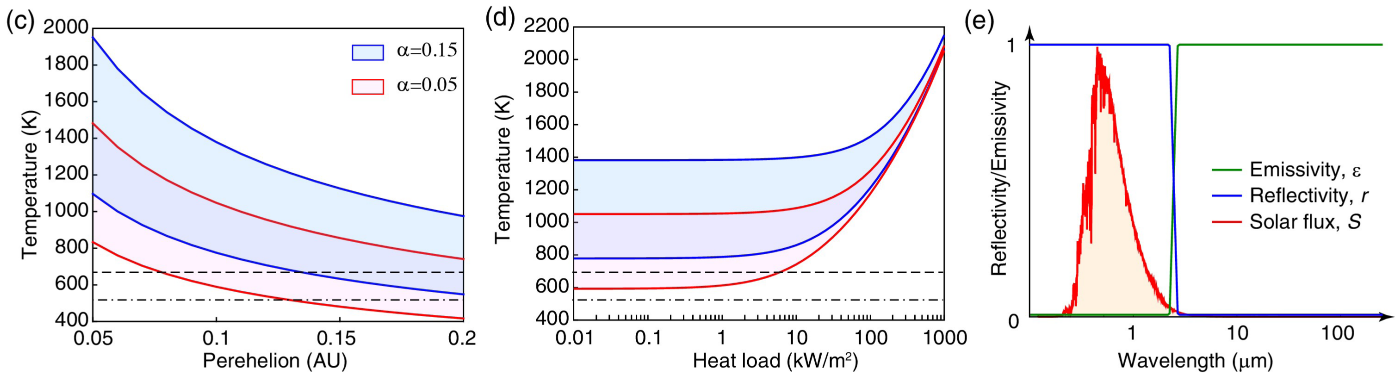


Figure 2-33. Design Spaces Possible for Sail Temperature at the Orbital Distance Closest to the Sun (Left); Sail Temperature Variation at 0.1 AU From the Sun for a Heat Load, Power (Middle); and an Illustration of an Ideal Reflectivity and Emissivity (Absorptivity) Spectra for the Sun (Right) *(Source: Davoyan et al. [136])*.

plasma interactions with nanophotonic structures, particularly thin-film heterostructures and the plasma's influence on the sail's structural stability and radiation reflection performance, is not understood. A diagram showing example effects of space-based damage on a multilayer sail material system is shown in Figure 2-34. In addition to energetic particles, micrometeoroids can cause punctures in sails.

Enabling Technology

Enabling technologies are in manufacturing, both sail and spacecraft specific, and lasers. The ability to manufacture thin films on very large-area substrates needs to be improved (to address larger, contiguous areas). This becomes more challenging as the materials become more esoteric than aluminum films (such as when metasurfaces are added). For supporting spacecraft structures, AM can be used to minimize excess mass and optimize structural booms and struts. In addition, lighter and stronger sail material and lighter/fewer boom/struts will ease the deployment process (prior mission failures and/or suboptimal results have highlighted the need for lighter motors and more reliable unfurling of the sail). In addition, present-day lasers have a limited useful range and are constrained by beam diffraction and laser aperture size. These limitations impose their own limitations on the acceleration distance for a solar sail design.

2.4.2.3 Space Tethers

Any material in LEO is subject to erosion from atomic oxygen from the high orbital speed and molecular strikes. In addition, micrometeoroid strikes are a concern. These actions can erode a tether, and any suitable materials need to be resistant to this. In addition, exposure to radiation degrades tether materials and reduces lifespan. Tethers that repeatedly traverse the Earth's Van Allen radiation belts may have markedly lower life than those that stay in LEO or are kept outside Earth's magnetosphere. These must be addressed in a tether material system.

Required tether properties and materials are dependent on the application. However, there are some commonalities. To achieve maximum performance and low cost, tethers need a combination of high strength, electrical conductivity (if an electrodynamic-type tether), and low density. All space tethers are susceptible to damage or destruction by space debris or micrometeoroids. Therefore, system designers need to decide if a protective coating is needed to protect against ultraviolet radiation and atomic oxygen.

For applications that exert high tensile forces on the tether (moment-transfer tethers), the materials need to be strong and light. Some tether designs

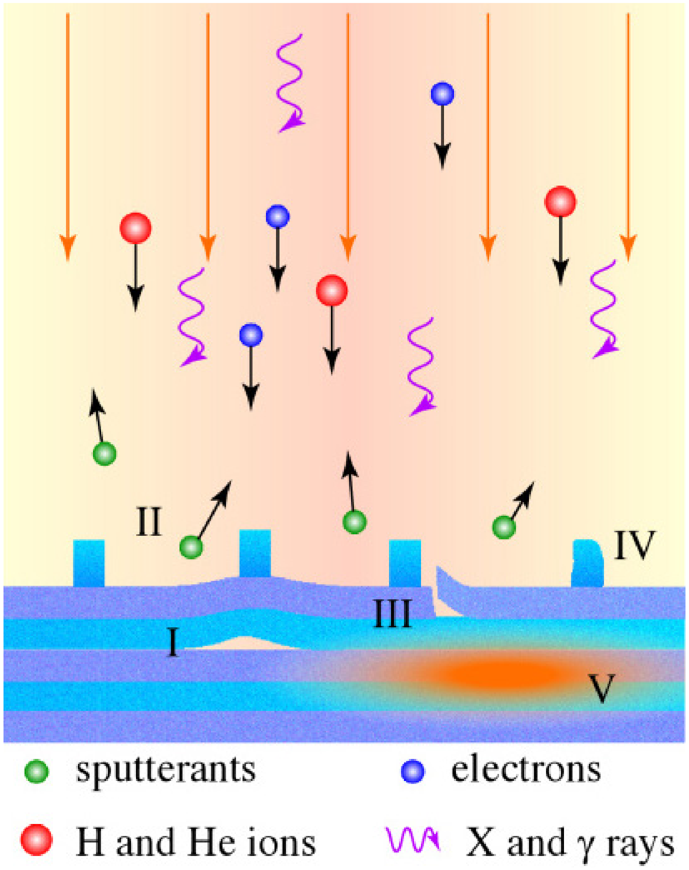


Figure 2-34. Effects of Solar Plasma, Energetic Photons, and Particles on Nanophotonic Structures: (I) Formation of Bubbles; (II) Surface Sputtering; (III) Cracking, Exfoliation, and Delamination; (IV) Surface Morphology Deformation; and (V) Energy Deposition Causing Thermomechanical Stresses *(Source: Davoyan et al. [136])*.

use crystalline plastics such as ultrahigh molecular-weight polyethylene, aramid (Kevlar), or carbon fiber. A possible future material would be carbon nanotubes, which have an estimated theoretical tensile strength between 140–177 GPa (20.3–25.6 Msi) and a proven tensile strength within the range from 50–60 GPa for some individual nanotubes. Other materials have been able to obtain 10–20 GPa in some samples on the nanoscale, such as monocrystalline whiskers made from graphite, alumina, iron, silicon carbide, and silicon. However, translating such strengths to the macroscale has been challenging, both in terms of producing pure monocrystalline materials in the macroscale and other issues associated with scaling up in size. As of 2011, carbon-nanotube-based fibers are an order of magnitude less strong than needed to make them practical for use in space tethers and do not offer any advantage over conventional carbon fibers on a macroscale [138–140].

For some applications, the tensile force on the tether is projected to be less than 65 N (15 lbf). Material selection in this case depends on the purpose of the mission and design constraints. Electrodynamic tethers, such as the one used on TSS-1R, may then be able to use thin copper wires to keep the tether as highly electrically conductive as possible while still staying within the mechanical constraints.

There are design equations for certain applications that may be used to aid designers in identifying typical quantities that drive material selection. One example is a space elevator equation that typically uses a characteristic length (L_c), which is also known as its self-support length and is the length of the untampered cable it can support in a constant 1-*g* gravity field.

One of the most recent uses of a space tether is on the TEPCE CubeSat mission operated by NRL [141]. The tether used was metal-coated, 9-strand, 200-denier Kevlar and Aracon. One material consideration that needed to be overcome was the unwinding of the tether in a safe manner. It was difficult to envision a reliable yet sufficiently weak adhesive brake, so brakes using bent pieces of 36-American-wire-gauge magnet wire were inserted in the winding. The strategy was to stretch the tether and cause fast unwinding at the end to dump energy into higher-frequency modes that could be damped faster (see Figure 2-35). The 1,030-m tether was wound on an 80-mm-long, 51-mm-diameter cup-like core that held the Stacer spring. The final winding was 86 mm in diameter and tapered 79–70 mm along the length. An image of the tethered spacecraft and an example of the produced current via the tethered material system is shown in Figure 2-36.

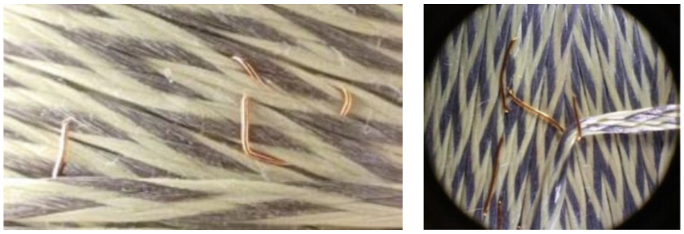


Figure 2-35. Tether Braking Hooks to Achieve Safe Payout Used on the TEPCE Cubesat Mission *(Source: Coffey et al. [141])*.

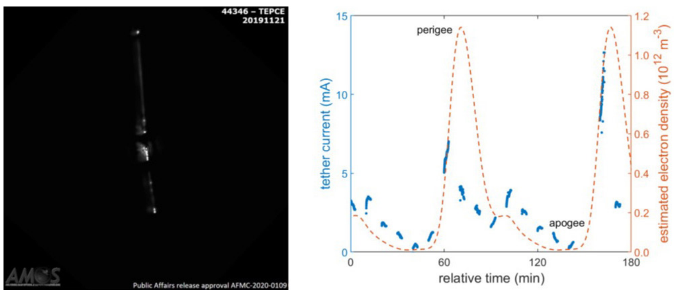


Figure 2-36. Image of TEPCE After Tether Deployment Taken at the Air Force Maui Optical and Supercomputing Site *(Source: Coffey et al. [141])*.

For TEPCE's composite tether material that tried to optimize conductivity and material's strength, communications and battery-life issues unrelated to the tether severely limited electrodynamic tether operations after deployment. Nonetheless, TEPCE was able to return relevant measurements. Current was made to flow in the electrodynamic circuit driven by the naturally occurring potential drop in the tether. Approximately 1 hr of current data was collected and transmitted per day of operation.

2.4.3 Future Technology Use

These nonpropellant-based technologies offer a number of different uses on future space missions.

2.4.3.1 Mass Drivers

Presently available mass-driver technology is ill suited for use on individual spacecraft but may provide a means to launch smaller spacecraft from larger bodies, especially when not constrained by an atmosphere (such as the moon, a space station, or asteroids). Research is likely to continue for terrestrial applications (such as weaponry). It is unclear when this technology can be transitioned to practical in-space use.

2.4.3.2 Solar Sails

Future progress beyond what is presently available for solar sailing will require the development of novel active and passive materials to meet demanding requirements of the space environment, sail control, and navigation. Davoyan et al. [136] produced a materials roadmap for this technology (see Figure 2-37).

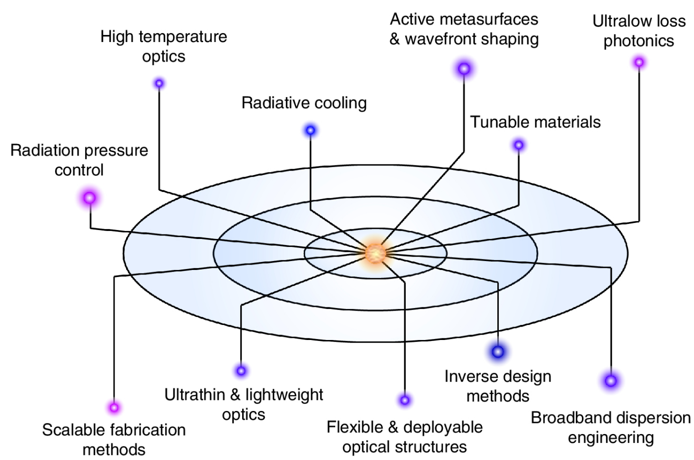


Figure 2-37. Technology Roadmap for Solar Sails With the Distance Indicating the Technology Readiness—The Farther Away From the Center (i.e., Present), the More Research Effort Needed *(Source: Davoyan et al. [136])*.

Thin-film photonic metamaterials and diffraction gratings may pave the way to novel multifunctional materials with enhanced capabilities for thermal management, reflectivity, and momentum control. Future high-temperature photonic materials may enable close solar flyby or use of high-power lasers for high-acceleration/deceleration missions. Metamaterials that can efficiently control the reflection and transmission properties may provide novel solutions for solar sail dynamics and attitude control. As mentioned, in addition to the sail materials themselves, this propulsion technology would benefit from more efficient architecture design and integration with lightweight support structures and deployment mechanisms.

Practically, scaling up in size is a concern, as it relates directly to availability of materials and mechanical strength. The sizes of sails flown to date have been relatively small, on the order of <200 m^2. Solar Cruiser, in development at NASA and expected to launch in 2025, represents a large increase to 1,672 m^2 (see Figure 2-38 for a reference). One item that must be addressed is how to scale to even larger sizes, such as 7,000 m^2 or even 28,000 m^2 to achieve accelerations of >1 mm/s^2. One material that may meet these requirements is graphene for novel, ultrathin/low-mass sails. However, producing this material in the sizes necessary is still an active area of research.

Figure 2-38. NASA's Solar Cruiser Sail (Made From a Flight-Proven Legacy Material—Thin-Film Polyimide [CP1] Coated With Aluminum) Unfurled to Show Its Size *(Source: NASA [142])*.

2.4.3.3 Space Tethers

Tethers offer a potentially low-cost and low-technology risk profile for a wide range of potential space propulsion missions. It is likely that near-term materials development will allow a greater range of deployment for these systems, and it is also likely that a composite tether material, such as the one deployed on TEPCE, offers the most immediate path forward to provide propulsion and power capabilities. Materials research needs to focus on producing materials in very thin- and long-form factors that have high tensile strengths. Until appropriate conductivity and tensile strengths can be achieved in the same material, metallics with structural tether material will be required to successfully achieve the propulsion goals.

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SECTION 03 KEY FUNDING AGENCIES

There are a number of funding agencies that are engaged in the development of space propulsion and associated materials.

3.1 NASA

The mission directives of NASA are to enable a safer, more secure, efficient, and environmentally friendly air-transportation system through aeronautics research; operate the International Space Station (ISS) and prepare for human exploration beyond LEO; explore the Earth-sun system, the world's own solar system, and the universe beyond; and develop the crosscutting, advanced, and pioneering new technologies needed for current and future missions, benefiting the aerospace industry and other agencies and addressing national needs. Within the scope of these goals, NASA provides a number of funding mechanisms to develop space propulsion technology materials.

3.1.1 Space Grants

NASA initiated the National Space Grant College and Fellowship Program, also known as Space Grant, in 1989. Space Grant is a national network of colleges and universities. These institutions are working to expand opportunities for Americans to understand and participate in NASA's aeronautics and space projects by supporting and enhancing science and engineering education, research, and public outreach efforts.

3.1.2 NASA Research Opportunities

NASA solicits science and technology research through the release of various research announcements in a wide range of science and technology disciplines. It uses a peer-review process to evaluate and select research proposals submitted in response to these research announcements. There have been topic areas within the solicitations for materials development for space propulsion.

3.1.3 Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs

The NASA SBIR and STTR programs fund the research, development, and demonstration of innovative technologies that fulfill NASA needs as described in the annual solicitations and that have significant potential for successful commercialization. There are topic areas within the solicitations for materials development for space propulsion.

3.1.4 ISS Funding Opportunities

There are several sources of funding available to scientists to be used for ISS research and development, payload development, payload processing at NASA facilities, on-orbit operation, and more. NASA funding for space-station use is obtained through NASA research announcements. National laboratory funding for space-station use is obtained through research opportunities with other government agencies, as well as with entities in the private and nonprofit sectors. Space propulsion has been included in this previously.

3.2 NATIONAL SCIENCE FOUNDATION (NSF)

NSF seeks revolutionary technologies to be deployed outside of Earth's atmosphere to enhance the commercial use of space. Technologies can include innovations that provide cheaper, safer, and more frequent products and solutions to commercial space customers. This topic particularly seeks to support growth-oriented small businesses that have not previously received significant SBIR/STTR funding and are seeking to contribute to economic growth by developing innovative technologies supporting the overall emerging space economy.

NSF funds proposals that address real capability gaps or enabling technologies for the space industry, anchored with a solid understanding of the challenges of working in space, including launch, mass, and volume restrictions; radiation and thermal environment; communications and latency; power and energy; etc. NSF encourages proposals with revolutionary satellite and vehicle hardware or systems innovations involving propulsion systems, navigation systems, and energy collection and power generation systems unique to space environments, in-space manufacturing systems, and services; Earth imaging and sensing; planetary (other than Earth) physical surveying, mapping, and prospecting services; extraction and processing of water and volatiles outside of Earth; and the search for extraterrestrial intelligence, space tourism, space weather, interplanetary habitats, and analytic algorithms based on data collected extensively from space-based systems, either alone or in combination with terrestrial systems.

Relevant technology possibilities include:

- SP4: In-Space Manufacturing Technologies
- SP5: Navigation and Positioning Technologies
- SP6: On-Orbit Technologies
- SP7: Remote-Sensing Technologies
- SP8: Spacecraft Development and Manufacturing
- SP9: Space Transportation and Access
- SP11: Other Space-Related Technologies

3.3 DOD

The DoD has funded a great deal of the space propulsion and materials science research in recent years. Of these, the USN and USAF have been the preeminent funding sources (this has not included the Space Force, as there have only been several years since the agency's inception). Figure 3-1 shows a breakout of research and development funding across DoD agencies as of 2022.

In addition, the recent surge in hypersonics research and the separately funded efforts by the USAF, Army, and USN to produce hypersonic vehicles means that there is significant, leverageable, technological funding between agencies that will act to further space propulsion materials science research (such as the necessary push for effective TPSs).

3.3.1 USSF

The USSF's FY23 budget request of $24.5 billion reflects the service's first real steps toward a more resilient force structure—including $1 billion slated for developing a new missile warning and tracking constellation with satellites in multiple orbits to complicate adversary attack.

The majority of the spending increase is aimed at overhauling how the Pentagon develops, buys, and structures its satellite fleets. The goal of the funding is to move away from reliance on small numbers of very expensive satellites to a more resilient force posture based on larger numbers of cheaper, dispersed satellites (which will require significant procurements of propulsion systems, large and small, both for launch, in-space maneuvering, and

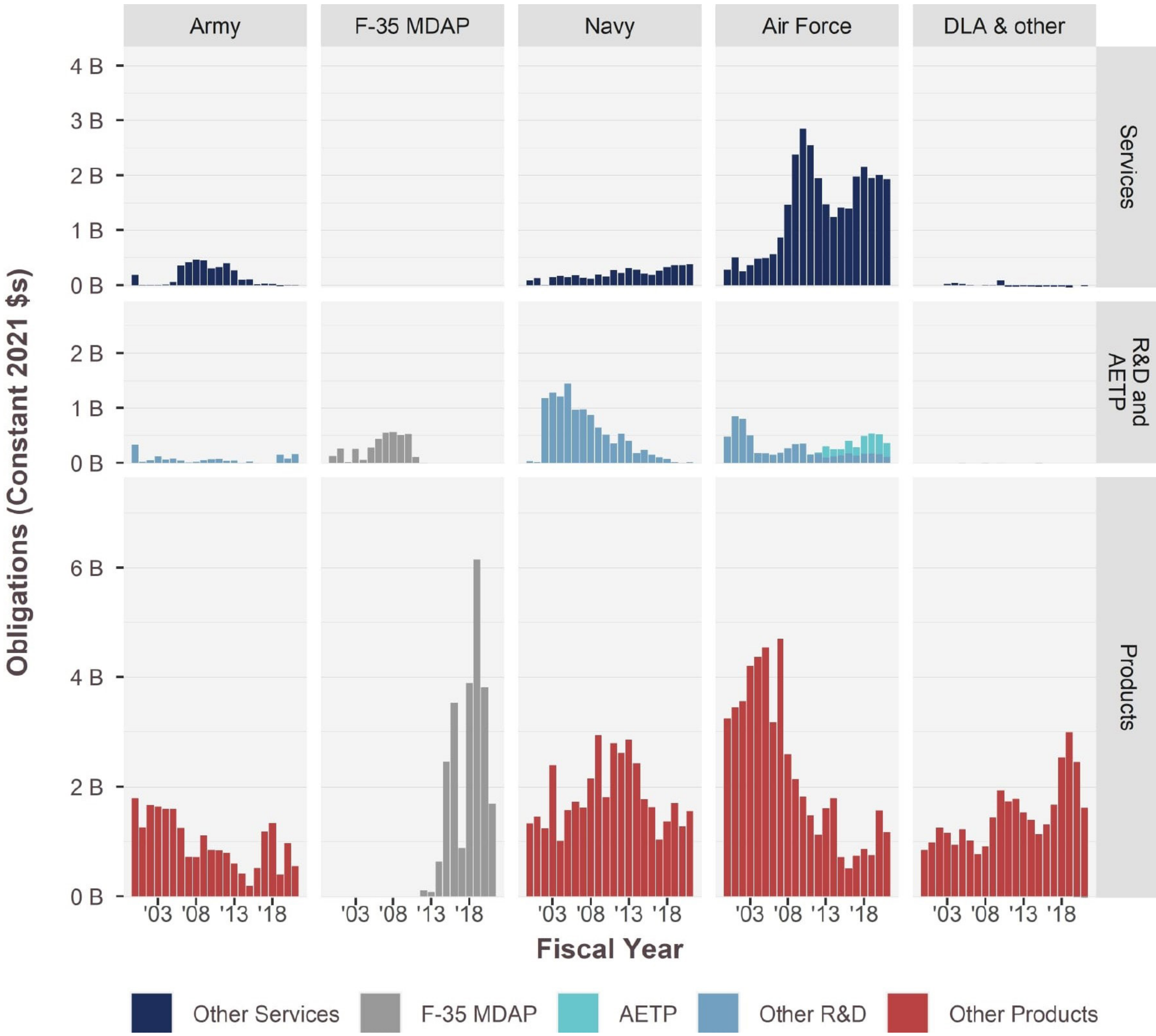

Figure 3-1. Contract Spending by Military Department in Services, Research and Development, and Products *(Source: Sanders and Velazquez [143])*

possibly eventual deorbiting). The slow pace of movement in that direction has been the subject of congressional criticism, and achieving this goal will be the service's top priority for the next decade [144].

3.3.2 USAF

Along with NASA, the USAF has been one of the primary funding entities for space propulsion research. One of the preeminent launch companies, SpaceX, received $33 million in funding from the USAF to assist with the development of the Raptor engines on the Starship launch system.

As a part of the Air Force Research Laboratory (AFRL), AFOSR has technical experts foster and fund materials for space propulsion research within AFRL, universities, and industry laboratories to ensure the transition of research results to support USAF needs.

3.3.2.1 Broad Agency Announcements

Broad agency announcements are used to communicate the needs and interests of the USAF. The USAF keeps specific requirements of each broad agency announcement up to date on grants.gov, the government's source to find and apply for federal grants.

3.3.2.2 Educational Programs

The scientific and technology departments of AFOSR, Business Integration Department, and the international office are responsible for management of programs that improve science and engineering education in the United States and stimulate interactions between USAF researchers and the broader international/domestic research community. These include, but are not necessarily limited to:

- Air Force Visiting Scientist Program
- Awards to Stimulate and Support Undergraduate Research Experiences
- Engineer and Scientist Exchange Program
- AFRL Science and Technology Fellowship Program
- USAF Summer Faculty Fellowship Program
- Window on Science Program
- Windows on the World Program

3.3.2.3 Special Programs

AFOSR provides support for research and education through the following unique programs:

- Historically Black Colleges and Universities and Minority Institutions Program
- Young Investigator Research Program
- STTR
- AFRL/AFOSR Center of Excellence

3.3.2.4 University Research Initiative Programs

The university research initiative programs are executed under the policy guidance of the Office of the Deputy Under Secretary of Defense for Laboratories and Basic Research to enhance universities' capabilities to perform basic science and engineering research and related education in science and engineering areas critical to national defense. These include:

- Defense University Research Instrumentation Program
- Multidisciplinary Research Program of the University Research Initiative
- National Defense Science and Engineering Graduate Fellowship Program
- Presidential Early Career Award in Science and Engineering

In addition, the USAF acts as an enabler for other branches of the DoD. As an example, the USAF has an informal agreement with the National Reconnaissance Office and National Geospatial-Intelligence Office to create joint requirements and cofund new space-based capabilities that can meet both intelligence and operational needs [145].

3.3.3 Missile Defense Agency (MDA)

The U.S. Missile Defense Agency funds space propulsion materials research via a number of different programs.

3.3.3.1 Advanced Technology Program Executive Office

The Advanced Technology Program Executive Office develops new system concepts and key components to ensure the missile defense system keeps pace with continually evolving threats. The advanced technology effort is focused on developing and demonstrating the next generation of technology that provides the capability to intercept across the battle space, discriminate in all phases of the kill chain, and reduce the number of interceptors required to defeat a raid.

3.3.3.2 Discrimination Technology

MDA's near-term goal is to add high-altitude airborne or space-based electro-optical sensors into the missile defense system architecture that can acquire, track, and discriminate ballistic and/or hypersonic missile targets. MDA is developing and testing these sensors on board unmanned aerial vehicles already deployed today.

3.3.3.3 Advanced Concepts and Performance Assessments

MDA established a "Smart Buyer" approach using model-based engineering tools and techniques. This includes assessing emerging missile defense needs, analyzing alternative concepts and technology, ultimately informing requirements, reducing risk, and ensuring cost-effective mission solutions.

3.3.3.4 University Research Programs

MDA funds colleges and universities to develop next-generation technology for possible implementation into missile defense systems. Research is ongoing in many technology areas, including minimizing the impact of debris, rapid-response architecture optimization, propulsion, electro-optical sensors, and materials characterization for space propulsion.

3.3.3.5 SBIR Program

The SBIR program harnesses the innovative talents of the nation's small technology companies for U.S. military and economic strength. The SBIR program funds early-stage research and development at these companies and is designed to stimulate technological innovation, increase private-sector commercialization of federal research and development, increase small business participation in federally funded research and development, and foster participation by minority and disadvantaged firms in technological innovation.

3.3.3.6 STTR Program

The STTR program is similar in structure to the SBIR program but funds cooperative research and development projects involving a small business and a research institution (e.g., university, federally funded research and development center, or nonprofit research institution). The STTR program creates an effective vehicle for moving ideas from research institutions to the market, where they can benefit both private sector and military customers.

3.3.4 DARPA

DARPA has worked specifically to develop higher-risk technologies. In addition, it has collaborated with other DoD and civilian agencies to enable the development of new technologies. As an example, its DRACO program is collaborating with NASA to build an NTR engine that could expand possibilities for the space agency's future long-duration spaceflight missions. The goal is to test an NTR-enabled spacecraft in Earth orbit during FY27. An NTR presents advantages over existing propulsion technologies, such as sending cargo to a new lunar base, sending humans to Mars, and sending robotic missions even farther.

3.3.5 USN

Although the USN is not typically thought of as a funding source for space-based propulsion, it operates one leg of the nuclear triad—the missiles to be launched from ballistic missile submarines in the event of an attack on the United States. Such a position means that there is funding from this branch that supports space propulsion research. In addition, NRL has also funded research into additional space propulsion mechanisms, such as the TEPCE CubeSat space tether mission. Also, the USN operates a very large number of nuclear reactors, which offer the ability to leverage research for nuclear thermal rocketry in the future. The USN participates in a number of the funding mechanisms described previously for the USAF, USSF, and MDA.

3.4 FOREIGN SPACE AGENCIES FUNDING PROPULSION RESEARCH

The four largest non-U.S. space agencies funding research into space propulsion are the ESA, the Chinese National Space Agency, the Russian Federation Space Agency (Roscosmos), and JAXA.

3.4.1 ESA

NASA and the ESA have collaborated for years in many fields, and materials development for space propulsion is one area where this takes place. ESA's Future Launchers Preparatory Programme (FLPP) identifies enabling critical launch system technologies to tackle these challenges and offers solutions via maturation of the TRL for future propulsion systems. Key technologies are designed at both the component and subsystem level prior to integration into demonstrator engines and testing in a relevant environment.

This approach has specific benefits such as:

- Offering a pool of options and upgrades for quick spin-offs applicable to existing launchers
- Performing high added-value research and development
- Safeguarding propulsion system integration and technology competencies in Europe

Within this framework, ESA is targeting several different propulsion technologies for development in the coming years.

3.4.1.1 Upper-Stage Engine Technologies

After the Vinci engine development was transferred to the Ariane 5 Midlife Evolution Development Program, the Expander-Cycle Technology Integrated Demonstrator (ETID) began mid-2013. This is a major constituent of FLPP and prepares competitive evolutions of upper-stage propulsion systems for Ariane 6 and Vega by assembling technologies that pave the way for the next generation of cryogenic upper-stage engines in Europe.

ETID addresses the following requirements:

- High Specific Impulse
- Low Cost
- Low Mass
- High Versatility
- Easy Integration and Control

This engine demonstrator combines several new technologies. Among them is an optimized combustion chamber design for maximum lifetime and heat pickup, which simultaneously avoids water condensation.

In addition, engine manufacturing aims for reduced production times and low cost and makes use of AM for the injector head, valve casings, and parts of the turbopumps. The nozzle and engine lines are designed for lower weight, making use of a sandwich nozzle with a radiative nozzle skirt, as well as novel materials. The valves are electrically actuated, and the engine controller is able to conduct automated checkouts and closed-loop-operation point control. The first full-scale demonstrator of the thrust chamber was tested at the DLR German Aerospace Center test facility in June 2018.

3.4.1.2 Storable Propulsion

The storable propulsion technology demonstrator helps develop technologies for a rocket engine in the thrust range between 3–8 kN. The technology developed in this project can be used in upper stages of small launchers or applications with similar thrust requirements, such as exploration missions or lander engines.

The demonstrator uses novel cooling, injector, and damping technologies. Future developments will investigate options to adapt the engine for the combustion of storable green propellants, which are more environmentally friendly and drastically reduce the necessary safety precautions for propellant handling.

3.4.1.3 Hybrid Propulsion

Hybrid propulsion offers a cheap and high-performance solution to power future operational space transportation systems by combining the benefits of solid and liquid propulsion. Initiated in 2010, the unitary motor propulsion demonstrator was developed within ESA's FLPP. A static firing in July 2018 proved the motor for its suborbital launch.

In September 2018, the Nucleus demonstrator for the hybrid-propulsion technology (a single-stage sounding rocket developed around the engine) was launched and reached an altitude of 115 km in less than 3 min, deployed 6 payloads, and then splashed down in the Atlantic Ocean. The hybrid engine combines liquid hydrogen peroxide with solid HTPB fuel and reaches a thrust of 30 kN (or 40 kN in vacuum). For greater performance, single motors can be clustered using a common oxidizer supply. A future version of the motor is planned to have an increased thrust of 75–100 kN, harnessing advanced turbopump technology. This is an important step toward using hybrid propulsion on orbital rockets, such as microlaunchers.

3.4.1.4 Solid Propulsion

Efforts concerning solid propulsion focus on the development of technologies for future motor casings and the investigation of the physics of SRMs, especially pressure oscillations via integrated demonstrators. The pressure oscillation demonstrator experimental is an experimental platform dedicated to the investigation of combustion physics and was test fired in cooperation with CNES in 2014, yielding valuable information into solid-propulsion combustion processes.

3.4.1.5 Methane Engine

Methane is a candidate for the propellant of the future. Combining high efficiency with operational simplicity while being environmentally friendly and widely available, it enables low-cost engine design for first- and second-stage applications. Compared to kerosene, methane causes no combustion residuals within the rocket combustion chamber and turbomachinery, which makes it a perfect candidate for a reusable booster engine. Prometheus (being developed by ESA and ArianeGroup) is an ultralow-cost reusable rocket engine demonstrator using liquid-oxygen-methane propellants with a thrust of 1,000 kN.

3.4.1.6 Future Work

Further project proposals for ESA are intended to focus on a reusability demonstrator for the next generation of launch vehicles to mature the relevant technologies' needed reuse of first stages or respective subsystems to lower launch costs in the future.

Moreover, a kick-stage demonstrator could address the need for increased versatility regarding mission profiles. Potential applications are payload injections into multiple orbits, geostationary transfer orbit GEO transfer maneuvers, as well as satellite servicing and debris deorbit applications. Electrically powered, pump-fed engines are an interesting technology to be considered in this context.

Another interest lies in the creation of a dedicated microlauncher to inject small payloads into custom orbits. This field will be addressed via feasibility studies. At the same time, multiple developments by private industry are currently taking place in Europe offering the long-term potential for spin-in solutions.

3.4.2 China National Space Administration (CNSA)

In competition with the United States and over the next five years, China plans to continue to improve the capacity and performance of its space transport system and move faster to upgrade launch vehicles. This includes further expanding its launch vehicle family, sending into space the next generation of manned carrier rockets and high-thrust solid-fuel carrier rockets, and speeding up the research and development of heavy-lift launch vehicles. The CNSA will continue to strengthen research into key technologies for reusable space transport systems and conduct test flights accordingly. China will develop new rocket engines, combined cycle propulsion, and upper-stage technologies to improve its capacity and efficiency when entering and returning from space [146].

China has launched many new technological test satellites and tested new technologies, such as the common platforms of new-generation communications satellites and very high throughput satellites' telecommunication payloads, which include Ka-band communications, satellite-ground high-speed laser communications, and new electric propulsion demonstrators and concepts.

In the next 5 years, China will focus on new technology engineering and applications; conduct in-orbit testing of new space materials, devices, and techniques; and test new technologies in the areas of:

- Smart Self-Management of Spacecraft
- Space Mission Extension Vehicles
- Innovative Space Propulsion Technologies
- In-Orbit Servicing and Maintenance of Spacecraft (China's Tianzhou-1 cargo spacecraft docked with the Earth-orbiting Tiangong-2 space laboratory and has claimed breakthroughs in key technologies for cargo transport and in-orbit propellant replenishment)
- Space Debris Cleaning

Specifics of these technologies are difficult to come by due to limited open-source information.

3.4.3 Roscosmos

In 2016, the Russian state space agency was dissolved and the Roscosmos brand became a state corporation, which had been created in 2013 as the United Rocket and Space Corporation. Roscosmos uses a family of several launch rockets, the most famous of them being the R-7, commonly known as the Soyuz rocket, which is capable of launching about 7.5 tons into LEO, such as to the ISS. The Proton rocket (or UR-500K) has a lift capacity of over 20 tons to LEO. Smaller rockets include the Rokot.

Currently, rocket development encompasses both a new rocket system, Angara, and enhancements to the Soyuz rocket, Soyuz-2 and Soyuz-2-3. Two modifications of the Soyuz, the Soyuz-2.1a and Soyuz-2.1b, have already been successfully tested, enhancing the launch capacity to 8.5 tons to LEO.

However, Russia is rapidly cutting itself off from much of the global space industry in response to sanctions due to the invasion of Ukraine. Space-focused research and investment firm Quilty Analytics sees U.S. companies as net beneficiaries, with SpaceX the clear winner in the global launch marketplace. Other companies providing space station services and developing new orbiting habitats are poised to benefit, with Iridium as a likely winner in satellite communications [147]. Recent quality-control issues with Soyuz modules leaking coolant when docked to the ISS may be linked to these deteriorating ties.

Other events of note affecting research are that, in March 2021, Roscosmos signed a memorandum of cooperative construction of a lunar base called the International Lunar Research Station with the CNSA. In addition, in April 2021, Roscosmos announced that it will be departing the ISS program after 2024. In its place, it was announced that a new space station (Russian Orbital Service Station) will be constructed with a projected start date of 2025 [147].

3.4.4 JAXA

JAXA has been involved in funding significant amounts of space propulsion, including electric propulsion and solar sails. It has focused on electric propulsion with a high specific impulse for satellite applications. When used as the final-stage motor of transportation systems, it is a key technology for deep space exploration. Research and development continues on a pulsed-plasma thruster and direct current arc jet. A magneto plasmadynamic arc jet was demonstrated on a Space Flyer Unit mission, and a microwave discharge-type ion engine was proven as the main propulsion of the asteroid explorer HAYABUSA [148].

As a future interplanetary propulsion system, research will focus on demonstrating the engineering feasibility of non-nuclear interplanetary exploration. As a means of future interplanetary flight, a solar electric sail to drive ion engines with high specific impulse is proposed. The feasibility of the solar electric sail has been promoted by the advent of lightweight and extremely thin-film technology. JAXA launched a small solar power sail demonstrator IKAROS for technological verification.

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SECTION 04 CONCLUSIONS

The number of possible propulsion technologies is increasing, and the available sets of materials to support development and deployment of existing and future technologies is increasing as well. Continuing this vital line of research is critically necessary, as the number of satellites needed to address the coming threats in the future will increase dramatically. Near-peer nations (especially the People's Republic of China) will continue to spend large amounts of money in this area in an attempt to pass U.S. technology. To continue U.S. dominance in space, progress in this technology area must continue.

Of particular interest is the means to continue to advance a number of these technologies by finding the means to scale them up (physically) so that they are able to provide greater Δv or they can drive ever-larger spacecraft. Also, many of these newer technologies need improvements to reliability to permit use on flagship missions or be deployed in mass on constellations of small satellites. To this end, there are several broad areas that need to be addressed for space propulsion from a materials perspective, as broken out by the general propulsion types.

4.1 CHEMICAL PROPULSION

For chemical propulsion, the primary material needs are:

- Manufacturability: This can take the form of scaling material up, to implementing AM for reducing mass, depending on the application. Further significant research needs to continue to be funded in this area.
- Development of New Propellants: This encompasses a wide range of topics from the development of green monopropellants to new solid-fuel mixtures. This can also include propellants that do not require special conditions for operation (such as room-temperature catalysts). In addition, depending on the propellant type, AM can be used to optimize fuel geometries (such as for solid propellants). Completely novel propellant mixtures that reduce the dependencies on exotic, supply-chain-constrained, or high-cost materials should also be pursued to harden the supply chain and ensure domestic materials sources can provide for all propulsion material needs.
- Development of Structural Materials: In chemical propulsion, high and sustained pressures are required. Constraining materials (such as for pressure vessels) can take the forms of improvements to traditional materials (such as aluminum or steel) or the implementation of composite-fiber polymer-reinforced material. This can also include nozzle materials, which require the ability to resist the very high temperatures associated with rocket exhaust. AM likely will have less of an impact for large rockets, due to the large sizes of pressure vessels, but can be leveraged for individual components and for smaller systems, both to reduce mass and increase efficiency. Development of high-entropy alloys containing

refractory components or refractory foams may offer a way to decrease nozzle mass while maintaining their desired features.

4.2 ELECTRIC PROPULSION

For electric propulsion, the primary material needs are:

- Manufacturability: Again, this can take the form implementing AM for reducing mass, depending on the application. Further significant research needs to continue to be funded in this area.
- Development of New Propellants: For electric propulsion, this means transitions to more commonly available materials (and moving away from xenon) to lower costs. Solid propellants may also need to be considered here. This also means improving the efficiency of these more commonly available or low-cost materials so that they are able to perform mission objectives that are now being addressed with exotic or higher-cost options.
- Development of Supporting Materials: This includes the ability to move away from more exotic materials to those that are cost affordable and not supply chain restricted. Systems that reduce the need to equalize charge between the ejected ions and the spacecraft body are desired.

4.3 NUCLEAR PROPULSION

For nuclear propulsion, the primary material needs are:

- Materials Selection: The fuel assembly, moderator assembly, control rod/drum assembly, and reflector assembly are all composed of a fairly set group of materials. There are a certain number of radioactive materials that must be used for this regardless of safety. Many of these, such as beryllium oxide in the reflector, may be able to have substitute materials developed to reduce cost and increase safety. Alternative materials are sought.
- Fuel: One of the biggest concerns with nuclear-powered spacecraft is failure near a population center and exposure to the nuclear fuel (a concern when NASA's Cassini mission was launched with 72 lb of plutonium in 1997). Research into materials that can provide further safety to fuel and help assuage public concerns regarding nuclear engines may also be necessary.

4.4 NONTRADITIONAL PROPULSION

For nontraditional propulsion, the primary material needs are:

- Manufacturability: This topic is wide ranging for this propulsion class depending on the specific type. One item that is common throughout is the ability to scale up. If a railgun is used, the ability to develop alloys in larger form factors as rail conductors is needed. To increase the acceleration capabilities of solar sails, significantly larger and contiguous sail sections need to be produced.
- Enabling Technologies: This can take the form of circuitry to allow seamless operation of a coilgun or motors and struts to ensure the smooth deployment of a solar sail. Advanced materials for solar cells presently do not have a manufacturing line for large-scale implementation.
- Testing: Test facilities for these propulsion schemes are often difficult to come by.

In summary, one key to further develop space propulsion technologies is for enabling technologies such as AM to continue to be researched in this area so that they can be leveraged over a wide range of assemblies, subassemblies, and components within a propulsion scheme. Exotic materials that are used in any space propulsion system or as a propellant (in particular, those that have a high cost or are supply chain limited or those that do not have a domestic source to ensure long-term strategic supplies) need to be identified, and research should be conducted to identify substitutes with more common materials or those that do not suffer from high costs or scarcity. In addition, steps need to be taken to ensure that any substitution does not result in performance degradation or loss of efficiency. Programs leveraging materials development in complementary areas (such as TPS for hypersonics) should be encouraged, and researchers in these areas should be linked with those performing exclusively space materials research.

Successful materials need to also be able to address the space-based environment—this means surviving for long periods while constantly being exposed to various types of radiation, charged particles, and B-fields while not experiencing material property degradation. In addition, terrestrial testing capabilities for propulsion technologies need to be nurtured and further developed. The United States operates many rocket testing sites, but for some types of propulsion (such as electric propulsion), true testing can only take place in a hard vacuum (with a very low number density), something that is not easily achievable within the inventory of the nation's vacuum chambers (when considering size, vacuum level, and number of available chambers). This becomes even more complicated for solar sails or other propulsion methods that produce thrust on the order of μN, which are difficult to test for within Earth's gravity and atmosphere.

With these suggestions in mind, funding must be found to ensure that materials research continues and to ensure that a robust workforce (both in industry and academia) exists to continue development, synthesis, production, and quality assurance of materials for this field into the future.

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