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Advancements in Propulsion Systems for Rocket Engines: A Review

Md. Abdullah [1], Tamanna Rahman [2], Subrata Saha [2], Md. Mosharrof Hossain [2],

[1]*Department of Space System Engineering, Bangabandhu Sheikh Mujibur Rahman Aviation and Aerospace University, Old Airport, Tejgaon Dhaka 1215, Bangladesh.*

[2]*Department of Mechanical Engineering, City University, Khagan, Savar, Dhaka-1340, Bangladesh.*

Abstract: - In recent years, there have been notable breakthroughs in rocket propulsion technology. The desire to improve efficiency, reliability, and versatility in the fields of space exploration and satellite deployment has motivated these advancements. This document provides a comprehensive summary of the latest advancements. Propulsion systems for rocket engines utilize it, emphasizing significant breakthroughs and their impact on space missions. Recent advancements in propulsion systems encompass a wide range of factors, such as propulsion techniques, engine configurations, materials, and control mechanisms. Ion and Hall effect thrusters are examples of electric propulsion systems that have greatly changed long-duration missions by offering better specific impulse and fuel efficiency than traditional chemical propulsion. Satellite station-keeping, orbit transfer, and deep space missions have utilized these systems. Furthermore, the development of sophisticated propellants, combustion technology, and engine designs has led to advancements in conventional chemical propulsion. Technological advancements, including additive manufacturing, have made it possible to produce intricate engine parts with improved accuracy and effectiveness. This has resulted in better performance and lower expenses. Additionally, researchers have focused their efforts on advancing reusable rocket technologies to lower launching costs and increase space availability. Significant progress in engine reusability, thermal protection systems, and landing techniques, as demonstrated by the successful deployment of reusable launch vehicles by many aerospace companies, has enabled the achievement of this aim. Furthermore, progress in propulsion systems has enabled ambitious space exploration missions, such as human-crewed expeditions to Mars, lunar exploration initiatives, and asteroid mining enterprises. Propulsion systems are essential for allowing spacecraft to travel long distances, move in space, and effectively achieve mission objectives. Recent advancements in rocket engine propulsion technologies have expanded the limits of space exploration, providing unparalleled prospects for scientific inquiry, business ventures, and global cooperation. This discipline's ongoing research and innovation have the potential to uncover additional improvements, thereby transforming the future of space exploration and usage.

Keywords*:* Propulsion systems; Rocket engines; Advancements; Electric propulsion; Chemical propulsion; Reusable rocket technologies

1. Introduction

Rocket engines serve as the fundamental driving force behind space exploration, propelling spacecraft to navigate extensive distances and investigate celestial entities outside of Earth. In recent years, there have been significant developments in rocket propulsion systems, motivated by the pursuit of improved performance, enhanced efficiency, and decreased prices. The rocket engine propulsion system plays a crucial role in supplying fuel to the engine and subsequently burning it to generate thrust. The system comprises many elements, including propellant tanks, fuel and oxidizing agent delivery systems, control mechanisms, and supply circuits. Its purpose is to ensure the stability, dependability, and effectiveness of the engine's operation.

During missions, the propellant supply system experiences structural loads, which necessitate thorough structural studies to validate and verify its integrity [1]. Occasionally, the propulsion system may incorporate electric drives for the engine pumps, electronic power and regulation control units, and accumulating devices such as accumulator batteries or supercapacitors. These components allow for cavitation stability, frequent activation, and enhanced thrust vector control [2]. The objective of the propellant-supplying system's design is to minimize the number of pipelines, overall construction, and weight while also reducing pressure losses in the flow of fuel and oxidizing agents [3]. Additionally, the exhaust gas circuit can enhance the pressure in the propellant tank by transporting exhaust gases from the combustion chamber [4]. In some rocket engine fuel systems, control valves connect several propellant storage compartments to make sure that extra propellant is added and that the carrying capacity doesn't drop [5].

A rocket engine's propulsion system operates by utilizing a blend of liquid propellant and combustion to produce thrust. Typically, the system comprises propellant tanks, a rocket engine that receives propellant via a pump, and a control system. An injector core expels the liquid propellant through the engine's structure, generating combustion gas [6]. The combustion chamber, characterized by its predominantly spherical shape, surrounds the combustion zone and exposes it directly to the combustion gas [7]. The propellant injector, situated next to the outlet, releases the liquid propellant into the engine's interior [8]. In the system, the combustion gas flow propels a turbopump, delivering fuel and oxidant to the pre-burner and primary combustor [4]. Additionally, we can utilize an exhaust gas circuit to transport exhaust gases from the combustion chamber to the propellant tank, thereby increasing their pressure. Rocket engines employ several sorts of propulsion technologies. One variant of the propulsion system incorporates electric motors for propellant pumps, enabling frequent activation and enhanced reliability in thrust vector management [2]. Another variant is a system with a combustion chamber and a propellant injector that sends cooling fuel along the chamber's wall [7].

Moreover, some systems incorporate an oxygen supply system, a hydrogen supply system, and an ignition unit to ignite the oxygen-hydrogen mixture inside the combustion chamber [9–10]. Additionally, a system with an electric motor serves as the primary power source for initiating, terminating, adjusting thrust, and modifying operational settings, thereby reducing the motor's workload [11]. Numerous rocket engine applications can utilize these diverse propulsion technologies, each offering distinct benefits.

Rocket propulsion systems have a range of benefits and drawbacks that vary based on the specific sort of system employed. Gel and hybrid propellant rocket systems, when used with appropriate propellants, provide advantages like reduced hazard potential, variable thrust, and simplified handling characteristics [12]. Thrust vector control systems, such as the bifunctional thrust vector control system (BTVCS), provide advantages in controlling a stage's flight by integrating mechanical and gas-dynamic control systems. By employing this technique, it is possible to achieve significant control forces while minimizing the loss of a particular impulse and ensuring great dynamic performance [13]. Another propulsion system uses a cooling duct to control the flow of oxygen, hydrogen, or a mixture of combustion gases in the combustion chamber, thereby improving the system's efficiency [10]. In addition, a rocket propulsion system that incorporates a liquid inert gas tank reduces the requirement for separate pumps to handle the oxidizer and fuel, thereby lowering complexity and enhancing efficiency [14]. Ultimately, a rocket propulsion system utilizes injectors and an ignition system to guarantee a uniform flow of oxidant and fuel throughout the injection and ignition stages, hence enhancing combustion [15].

Rocket engine propulsion systems are getting better by using machine learning and related techniques, nozzles that cool themselves, thrust chambers made of ceramic matrix composites (CMC) that cool themselves through transpiration, and reducing the amount of extra work that needs to be done on business processes. Propulsive applications utilize machine learning techniques to enhance performance and gain a deeper understanding of intricate physics [16]. Researchers are currently using additive manufacturing techniques to create regeneratively cooled nozzles, aiming to simplify the process and reduce expenses [17-18].

These improvements address issues related to the availability of accurate and detailed data, the complexity of manufacturing processes, and the need for improved performance, safety, and environmental reduction. Propulsion systems for rocket engines exhibit diverse levels of efficiency, cost, and reliability. Hybrid propulsion systems, which utilize a combination of liquid oxidizer and solid fuel, have benefits in terms of cost and flexibility [19]. ONERA and other groups have conducted thorough studies and optimizations of these systems using a combination of experimental testing and numerical simulations [11]. Electric rocket engine systems employ an electric motor to initiate, terminate, regulate thrust, and modify operating conditions. This leads to a decrease in battery weight and a simplification of control mechanisms [20]. Additive technology has enhanced propulsion systems, leading to advancements in mass-energy properties and cost-efficiency [21].

Various propulsion technologies, including propellers, turbojets, rockets, and turbofans, possess distinct performance characteristics and involve trade-offs in terms of efficiency and speed capabilities [22]. Additional inquiries and computational simulations are required to acquire more refined design options for hybrid rocket engines. Future advancements in propulsion systems for rocket engines have the potential to completely transform space exploration. Africa has already acquired expertise in beam energy propulsion, green propulsion, breakthrough propulsion, the ability to create nuclear thermal propulsion (NTP), and solar sail propulsion [23]. The development of rocket engines throughout history has laid the groundwork for future progress, as scientists and engineers have investigated different types of propellants and designs [24]. Electric propulsion, such as airbreathing magneto plasma dynamic (MPD) thrusters, exhibits potential for utilization in atmospheric settings. However, additional study is required to solve safety concerns [25]. Liquid rocket engines have the advantage of being able to restart and adjust their thrust, which makes them well-suited for applications such as hybrid rocket propulsion and other space-related uses [26]. Reusable launch systems, 3D printing, and additive manufacturing are making spacecraft and launch vehicles more cost-effective and efficient [27]. The potential of these upcoming advancements in propulsion systems lies in their ability to improve efficiency, lower expenses, and broaden the horizons of space exploration [28].

2. Traditional liquid propulsion systems

Traditional liquid propulsion systems are rocket propulsion systems that use liquid fuel and oxidizer as propellants. Since the dawn of the space age, all significant space missions have relied on these systems. The meticulously synchronized parts of liquid-fueled rocket systems regulate the propellant flow from storage tanks, transport them at the necessary pressures, and inject them into the combustor [29]. These systems need to take into account a number of factors, including propellant selection, cryogenics, engine performance, engine cycles, propellant supply systems, liquid propellant, turbopumps, thrust chambers, and unconventional engines. Mechanically and fluidically, these systems are highly interconnected [30].

The performance of the liquid fuel propulsion systems in next-generation space systems will determine whether they succeed or fail [31]. Throughout history, conventional liquid propulsion systems have experienced substantial improvements and innovations. Applications, engine cycles, and propellant combinations categorize engines in the realm of liquid rocket engines. Researchers have studied, tested, and flown different mixtures of liquid propellants [32]. Table 1 shows an overview of recent work on traditional liquid propulsion systems.

1. **Table 1: An overview of recent work on** traditional liquid propulsion systems.

SL	Year	Findings	Reference
1	2016	The downsizing of gas generator cycles presents challenges for rocket engine systems and staged combustion cycle engines.	[128]
2	2019	Particles of aluminum improve the way hydrazine fuel burns. The ideal level of aluminum solid loading is six weight percent.	[129]
3	2022	Micro hybrid rocket motors can produce large amounts of power. At first, there is more safety during operation and production.	[130]
4	2003	The vortex chamber concept improves the efficiency of combustion. Cooler propellant streams pass along the chamber wall, eliminating the need for cooling procedures.	[131]
5	2011	Small rocket engines use CCCM in the combustion chamber. We are designing a dependable connection for engines with a metal mixing head.	[133]
6	2022	Additive manufacturing offers significant cost and time reduction benefits for liquid rocket engines. Applying additive manufacturing to	[132]

		liquid rocket engines still presents challenges regarding size range, material limitations, and surface roughness.	
7	2012	Paraffin-based fuels exhibit impressive regression rates for hybrid rockets. Combustion involving a liquid layer result in a higher rate of mass transfer.	[134]
8	2017	Propulsion systems for missiles include solid/liquid-fuel rockets, ramjets, and scramjets. DRDL in Hyderabad has successfully developed a state-of-the-art scramjet test facility for the HSTDV programmed.	[135]

Liquid rocket engines, the principal propulsion of space launch vehicles and early ballistic missiles, have made significant advancements in space exploration possible, including visits to the moon and beyond Earth's orbit [33]. In the marine sector, the conveyance of liquids has progressed from the use of drums as cargo to the integration of tanks into ship structures [34].

Technological developments have led to the creation of propulsion systems for tankers operating in ice conditions, such as electric propulsion systems with podded propellors and fixed-pitch and controllable-pitch propellers [35]. These developments have made it possible for tankers to operate in difficult areas and perform better on ice [36]. Internal combustion engines, one of the more common forms of traditional liquid propulsion, are facing difficulties because of their detrimental effects on the environment. Because of their potential to lower emissions and increase efficiency, contemporary options, including electric motors and hybrid power systems, have drawn attention [37]. Figure 1 presents sources of noise and vibration on a modern aft-mounted prop-fan [33].

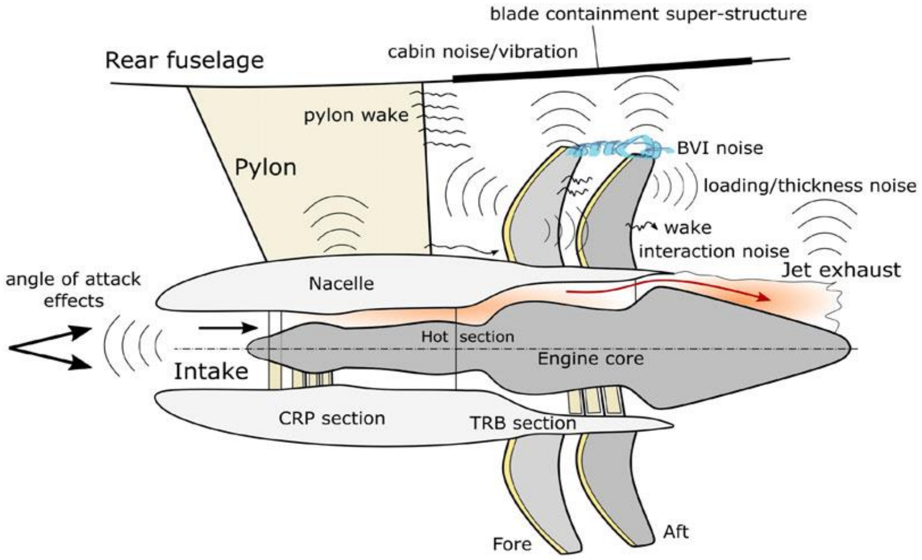


Figure 1: Sources of noise and vibration on a modern aft-mounted prop-fan [33].

In particular, electric motors have benefits including cheap maintenance costs, powerful performance, zero or very little emissions, and excellent efficiency [38]. They do have several drawbacks, though, including a low range and no infrastructure for charging [39]. It is necessary to compare various propulsion systems, taking into account aspects like power, range, cost, and environmental impact [40]. Despite recent great strides, electric propulsion systems still have issues with energy density and range when compared to conventional liquid propulsion systems [41]. All things considered, the future of alternative propulsion systems is bright, with continuous technological improvements in electrical components and rising affordability. Reducing greenhouse gas emissions and adhering to environmental standards are two of the main issues in the design and operation of classical liquid propulsion systems [42–43]. Figure 2 shows mechanical conversion loss [38].

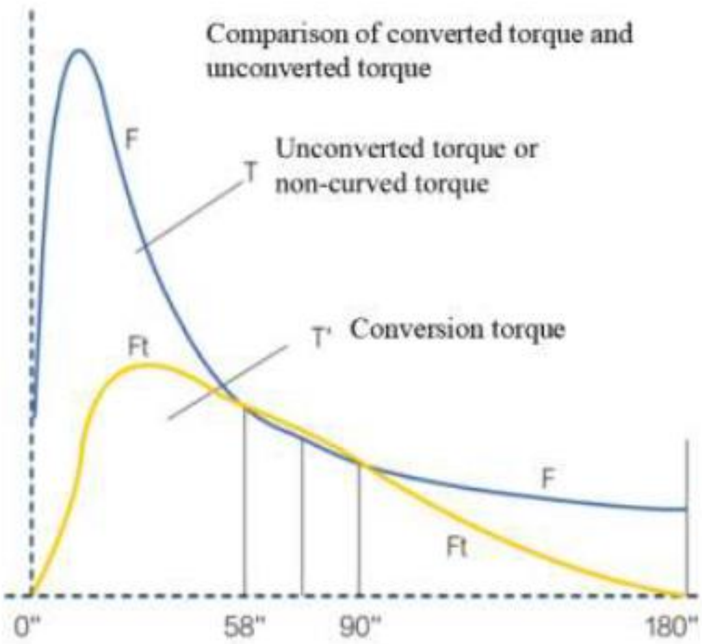


Figure 2: Mechanical conversion loss [38].

This necessitates the creation of greener and more efficient power systems, like using electricity as the primary energy source [44]. In order to comply with regulations and lower greenhouse gas emissions, ships must also reduce their environmental impact and increase energy efficiency [45]. It can be anticipated that innovations in marine power systems will create new economic opportunities and contribute to a greener world in the future [46]. The work tackles the challenges and complexities of structural dynamics in huge thrust liquid rocket engines, in addition to providing insights and solutions for many dynamic concerns faced in engine development [47]. To further reduce emissions and reach the objective of zero-carbon shipping, the development of cutting-edge technology, such as hybrid propulsion systems and alternative fuels, will be essential. Figure 3 shows mechanical conversion loss [41].

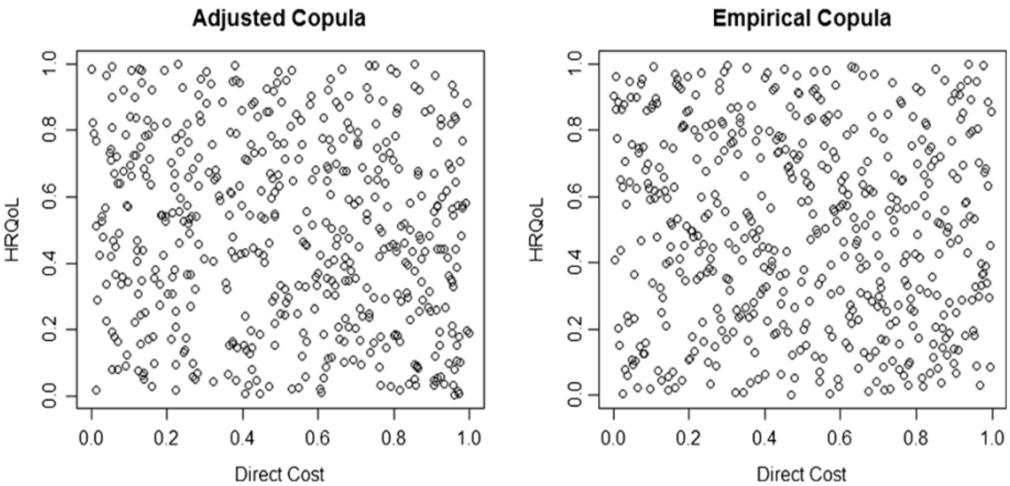
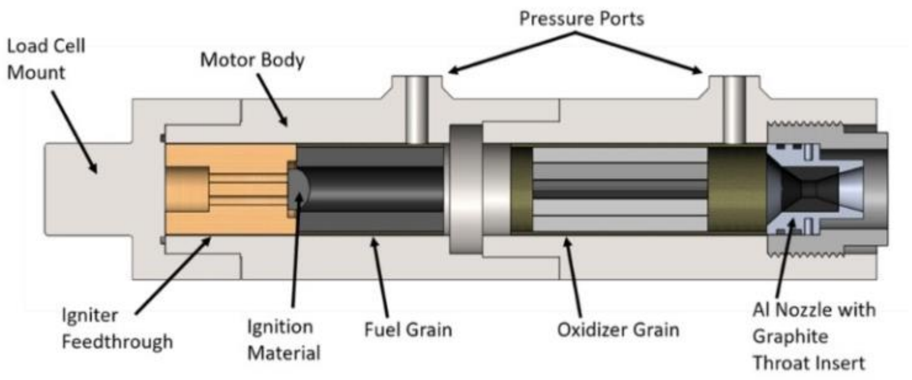


Figure 3: Mechanical conversion loss [41].

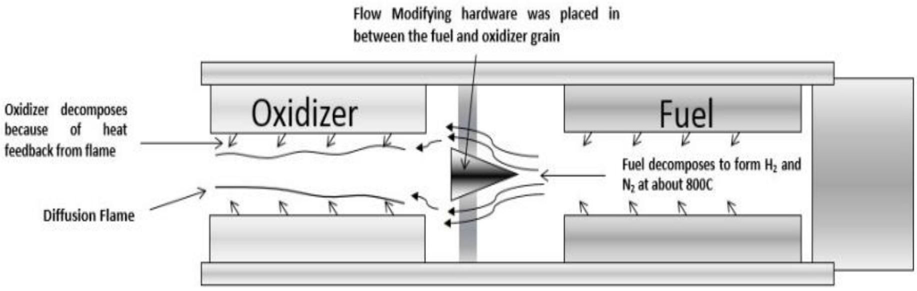
3. Solid propulsion systems

Rockets with solid propulsion systems use machinery to move previously motionless bodies. These systems typically burn fuel to produce high-pressure, high-temperature gases, which they then release through a nozzle to produce thrust. For solid rocket motors to endure the pressure and heat loads produced during combustion, careful design and construction are essential. Recent advances in propellant chemistry have led to the development of fuel-rich molecules capable of storing large amounts of hydrogen, resulting in the creation of a novel segregated propulsion system. By physically separating the fuel and oxidizer, this technique improves safety and makes it possible to use materials with a higher energy content. Rocket design and knowledge of energy conversions can help optimize a rocket's thermal and propulsive efficiencies, which define its total efficiency [48-50].

Rocket propulsion systems with solid propellant have a number of benefits and drawbacks. Their simplicity, affordability, and dependability are some of their benefits, which make them appropriate for a range of uses, including primary propulsion units and boosters [48]. Additionally, they are capable of producing a lot of thrust, which makes propulsion effective [51]. Solid-propellant rockets do have certain limits, though. Their usefulness in space propulsion is limited because they are unable to stop and resume thrust production [52]. Furthermore, chemically active conditions can erode the nozzle throat, reducing rocket force and impairing motor function [53]. Comparing this to hybrid rockets, another drawback is the restricted control over thrust and specific impulse [54]. Solid propulsion systems are still in use today despite these drawbacks because of their affordability, dependability, and ease of use. Systems for solid propulsion have many benefits over those for liquid propulsion. Because of their simpler construction, solid rockets can serve as apogee kick motors for orbit insertion and launchers [48]. Figure 4 shows that a) schematic of segregated solid propulsion system (SSPS) static testing motor. b) schematic of flow distribution effects using a flow modifier between grains [48].



a)



b)

Figure 4: a) Schematic of segregated solid propulsion system (SSPS) static testing motor. b) Schematic of flow distribution effects using a flow modifier between grains [48].

Physical separation between the fuel and oxidizer allows for the use of higher-energy ingredients without increasing sensitivity, contributing to their reputation for superior safety [51]. Furthermore, fuel-rich product gases from the self-sustaining breakdown of solid propellants can mix with solid oxidizers to produce high-temperature gases [55]. However, satellites frequently employ liquid propulsion systems because of their ability to stop and resume thrust generation [56]. The ability to use environmentally friendly propellants with reignition and throttling capabilities is another benefit of liquid propellants [54]. Liquid propulsion systems give greater flexibility and control over thrust generation; however, solid propulsion systems generally offer a higher level of safety and simplicity. Recent years have seen breakthroughs in solid rocket propulsion technologies. One advancement is the idea of distinct solid oxidizer and hydrogen rich solid propellant grains, which permit the use of greater energy ingredients without sacrificing safety [48]. Research and development of cutting-edge space propulsion technologies, such as beam energy propulsion, green propulsion, breakthrough propulsion, nuclear thermal propulsion (NTP), and solar sail propulsion, is another development.

These technologies offer reduced costs, improved efficiency, safety, and dependability, as well as emissions that are less harmful to the environment [23]. Furthermore, the simplicity, safety, and throttle and restart capabilities of hybrid rocket propulsion have drawn attention, making it a viable option for a range of space applications [26]. Figure 5 shows stress and strain curve of solid propellant [59]. These developments, which enhance performance, safety, and efficiency while placing Africa in the global space market, have the potential to benefit future space exploration missions [57]. Electric, laser, and nuclear rocket engines are also considered viable substitutes for chemical propulsion systems in interplanetary and interstellar travel [58]. For solid rocket propulsion systems utilized in planetary exploratory missions, decontamination is required. Prospective results indicate that researchers are exploring novel approaches to reduce biological burdens [59]. There are limitations to the specific impulse performance of solid rocket propulsion. One potential workaround for limitations is ammonium dinitramide, or ADN [60].

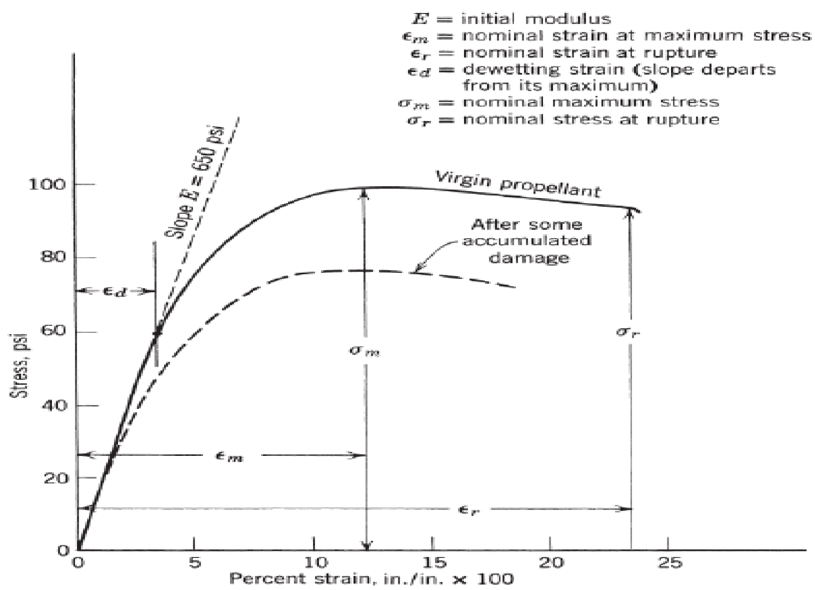


Figure 5: Stress and strain curve of solid propellant [59].

Benefits of hybrid rockets include reignition, throttling, and environmentally friendly propellants. Estimating fuel consumption and optimizing thermal insulation material performance are the issues [54]. Heavy lift space launch vehicles performed better because of additional boosters and heavier propellers. Patents and published studies [61] demonstrate the advancements made in space propulsion systems. Solid rocket propulsion has special characteristics, yet its specific impulse performance is limited. AND based formulations have the potential to improve performance or lessen their negative effects on the environment [62]. Figure 6 shows solid rocket engine [61].

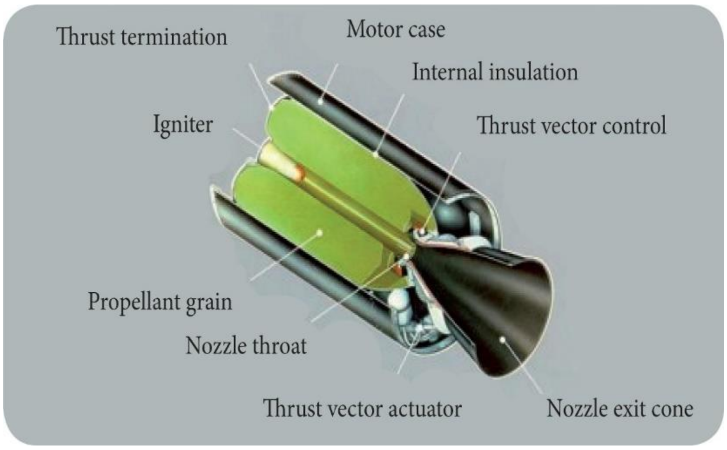


Figure 6: Solid Rocket Engine [61].

4. Electric propulsion systems

Electric propulsion systems for rocket engines utilize electric power to propel spacecraft. These systems encompass various types such as electrothermal, electrostatic, pulsed, and magneto plasmo dynamic thrusters [63]. They typically consist of components like electric pumps, turbines, gas generators, and motors, which work together to generate high-pressure gas for thrust [11, 64]. The electric drives in these systems enhance reliability, simplify control, and reduce battery weight, facilitating rocket recovery [2, 65]. Different thruster systems offer specific characteristics like high efficiency, specific impulse, and thrust cost, allowing for mission-specific selection based on factors such as power budgets and cargo weight. Overall, electric propulsion systems represent a crucial advancement in spacecraft propulsion technology, offering versatility and efficiency for various space missions.

Electric propulsion systems used in rocket engines encompasses various types. These include electrothermal, electrostatic, pulsed, and magneto plasmo dynamic thrusters [64-65]. Examples of these systems range from Hall thrusters to ion thrusters, DC heated Resistojets, Arcjets, Field emission electric propulsion thrusters, and more [8,11]. Additionally, innovative designs like VASIMR, Colloid and Electrospray thrusters, and High efficiency multistage plasma thrusters are part of this array [66]. These systems differ in their mechanisms for imparting kinetic energy to propellant, affecting factors like specific impulse, thrust cost, and propellant type. The choice of propulsion system depends on mission requirements such as cargo weight, power budgets, and simplicity, highlighting the versatility and adaptability of electric propulsion systems in modern spacecrafts. Electric propulsion systems offer various advantages over traditional chemical propulsion systems in terms of efficiency, environmental impact, and future trends. Research compares fully electric and hybrid marine propulsion systems, highlighting the benefits of waste heat recovery and hybrid turbochargers for efficiency enhancement [67]. Figure 7 shows rocket engine system composition with electric as subsystem [63].

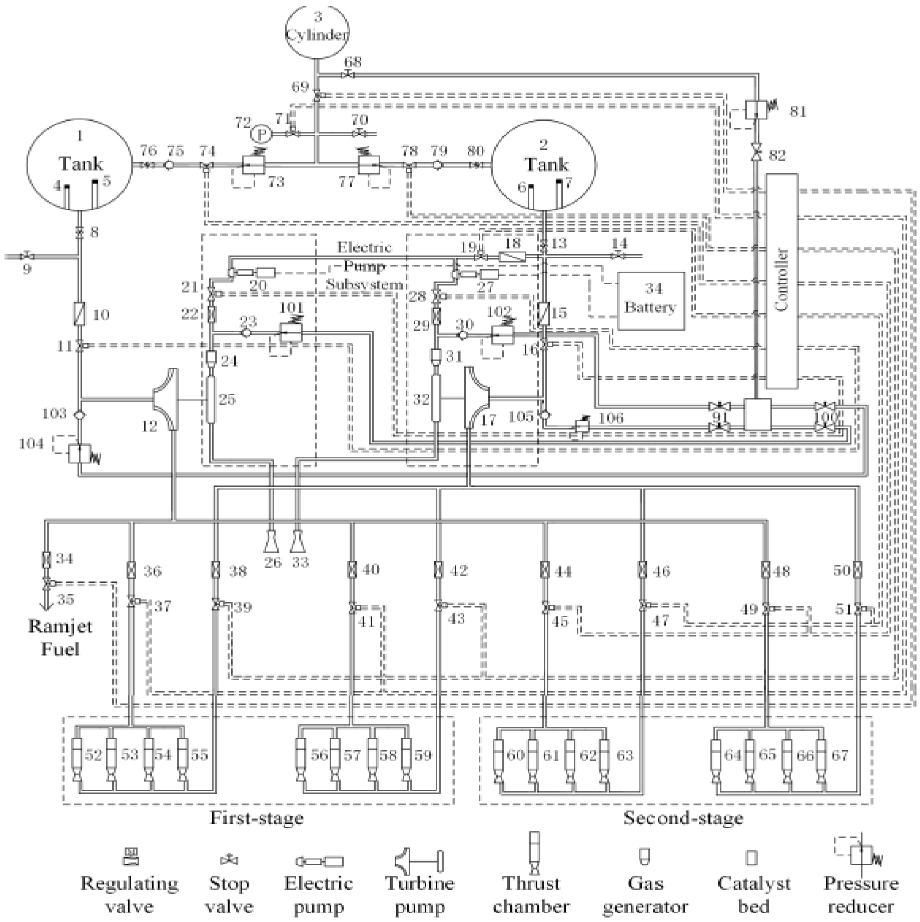


Figure 7: Rocket engine system composition with electric as subsystem [63].

Additionally, advancements in electric propulsion include various types like electrothermal, electrostatic, and electromagnetic systems, offering flexibility based on mission requirements [37]. Novel designs in electric propulsion focus on improving environmental performance, with systems utilizing electric capacitors for thrust generation [65]. Despite challenges like mass and size limitations, efforts to reduce the weight and dimensions of electric propulsion systems are ongoing, emphasizing the importance of synchronous generators for improved performance and compatibility [68]. Overall, electric propulsion systems demonstrate superior reliability, maneuverability, and safety compared to traditional chemical propulsion systems, aligning with the trend towards electrification in automotive engines [69].

Advancements in electric propulsion systems for rocket engines include the integration of technologies such as high-speed electric pumps, electrical turbopumps with coolant bypass ports, and electric motor-driven systems for thrust control and adjustment [11, 63, 70]. These innovations aim to enhance efficiency, performance, and reliability while reducing overall system mass and improving engine regulation capabilities. Additionally, research is exploring the use of lasers to increase thrust and fuel efficiency in rocket propulsion systems, with a focus on simplicity, cost-effectiveness, and practicality [71]. Developers are continuously exploring various technologies and approaches to enhance the performance and safety of electric propulsion systems for rocket engines [72].

5. Nuclear propulsion systems

A Nuclear Propulsion System for a rocket engine involves utilizing nuclear energy to heat a fluid, typically hydrogen, which is then expelled through a rocket nozzle to generate thrust. This system offers higher fuel efficiency, greater mission range, and the ability to abort missions safely. It has been studied extensively since the

1950s and is being considered for crewed missions to Mars by NASA. The system includes a reactor containing fissionable material, a neutron source, and a design to confine the fission reactions and heat transfer to the fluid for propulsion [2, 73]. Additionally, advancements in energy collection, storage, and utilization systems are being explored to enhance the specific impulse and thrust of rocket engines for deep space exploration and other space missions [74]. Ground testing of Nuclear Thermal Propulsion (NTP) engines poses unique challenges due to environmental regulations, necessitating innovative approaches for testing to mitigate health and safety risks [75-76].

A Nuclear Propulsion System in a rocket engine operates by utilizing nuclear reactions to generate energy for propulsion. The system typically consists of a reactor containing fissionable material and fuel pebbles, a neutron source for initiating fission reactions, and a fluid for moderating neutrons and transferring heat [77]. Figure 8 shows recession rate of U 0.1 Zr 0.9 C compared to other uranium compounds and refractory carbide materials [75]. The reactor heats the fluid, which is then expelled through a nozzle to produce thrust [73]. Different types of nuclear propulsion systems exist, including naval, aero-nuclear, and space nuclear propulsion, each offering unique advantages such as increased range, speed, and efficiency [2]. Nuclear rockets can employ either open thermodynamic cycles for thermal rockets or closed cycles for electric systems, with the former discharging the working fluid after a single pass through the engine and the latter continuously circulating the fluid while incorporating radiators for waste heat rejection [78].

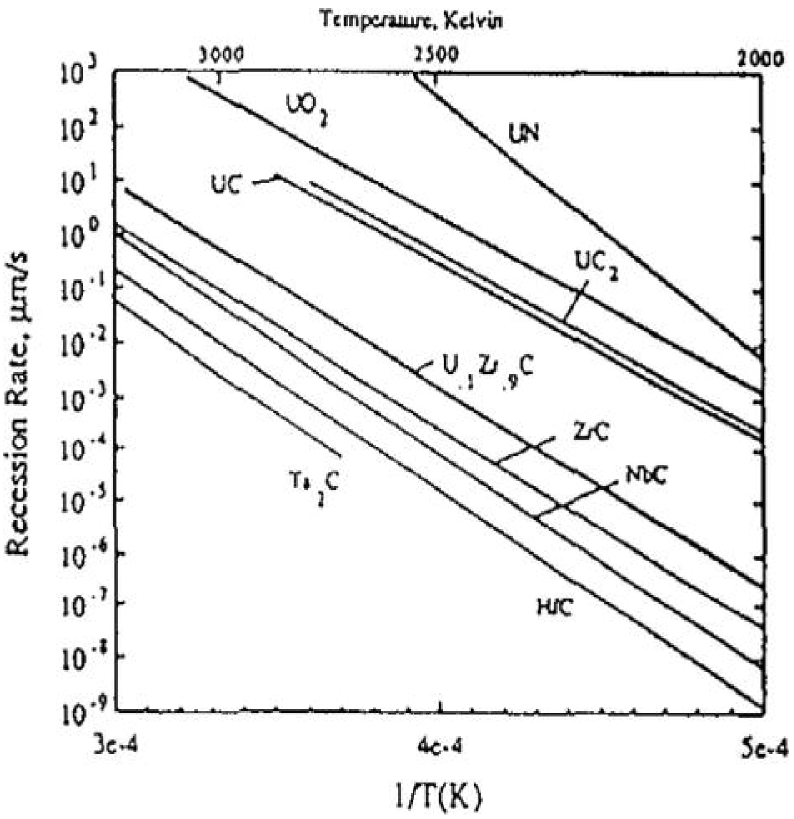


Figure 8: Recession rate of U 0.1 Zr 0.9 C compared to other uranium compounds and refractory carbide materials [75].

Nuclear propulsion systems offer several advantages over traditional rocket engines. They provide increased range, speed, and maneuverability for naval applications [79]. In space exploration, Nuclear Thermal Propulsion (NTP) systems offer higher fuel efficiency, greater mission range, shorter transit times, and enhanced mission abort capabilities [78]. Figure 9 shows nuclear Thermal Propulsion Engine Exhaust Total Containment Concept [76].

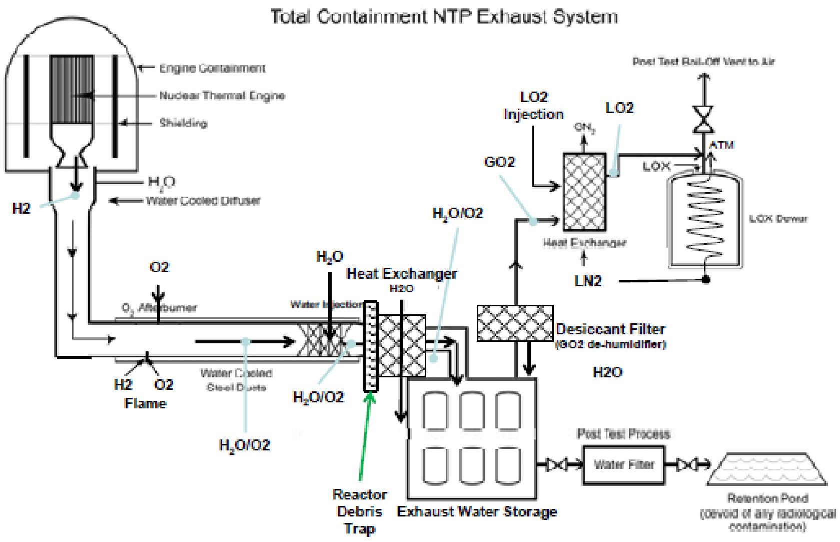


Figure 9: Nuclear Thermal Propulsion Engine Exhaust Total Containment Concept [76].

However, challenges exist, such as the need to develop extremely high-temperature reactors for space nuclear propulsion [75]. Additionally, the harsh operating conditions of NTP systems present significant design and operational challenges [2]. While nuclear rocket motors can improve the design characteristics of space missions, their high cost makes them less feasible for near-Earth transport operations compared to traditional rocket engines [80]. Overall, nuclear propulsion systems offer superior performance benefits but come with specific technical and cost-related drawbacks. The development of Nuclear Propulsion Systems has significantly impacted the space exploration industry by offering enhanced performance benefits over traditional propulsion systems [73, 81]. Nuclear thermal propulsion (NTP) systems, utilizing nuclear fission to heat hydrogen for thrust, provide higher fuel efficiency, greater mission range, shorter transit times, and increased mission abort capabilities [82]. NASA is evaluating NTP for crewed missions to Mars, with plans for a potential mid-2020s flight demonstration [83]. Additionally, the Fission-Powered Pulsed Plasma Propulsion concept presents a compact, high-efficiency spacecraft design, avoiding complex assembly and reducing mission times, thus potentially revolutionizing manned space exploration [84]. Figure 10 shows particle or droplet liquid fuel reactor [77].

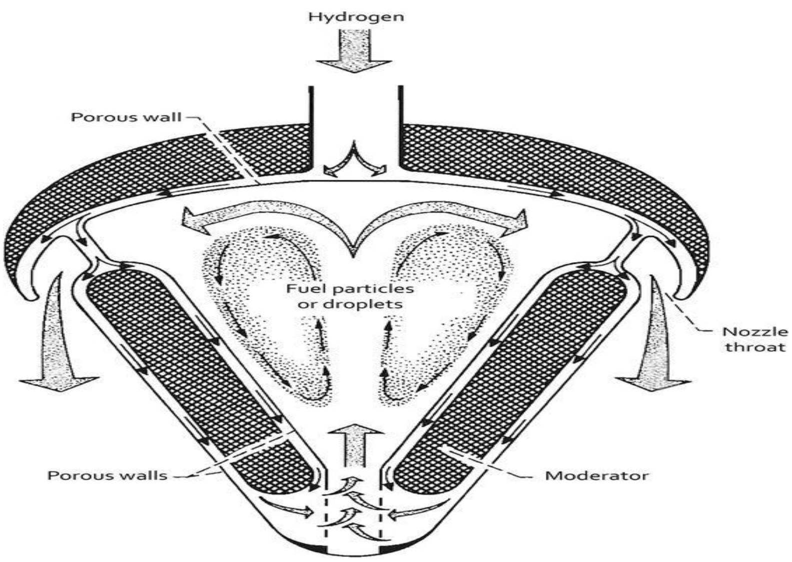


Figure 10: Particle or droplet liquid fuel reactor [77].

The integration of nuclear propulsion technologies into space missions opens up new possibilities for more efficient and ambitious space exploration endeavors. USNC-Tech specializes in nuclear power and propulsion technologies for space travel and permits self-sufficiency and impactful science missions in space [75]. NTP makes faster space exploration with bigger payloads and lower expenses possible. The first-generation NTP system offers high thrust and performance improvement [85]. There are applications and consequences for nuclear energy in space travel. It can be utilized as a power source and propulsion for space missions [86]. Compared to chemical engines, NTP offers double the specific impulse and higher thrust. Future high-performance systems are built on the foundation of first-generation NTP systems [87].

6. Applications and future directions

Rocket propulsion systems have diverse applications and promising future directions. Electric space thrusters offer advantages over chemical thrusters, enabling longer mission lifetimes with lower weight and propellant consumption [88]. High-energy systems are exploring new fuels and utilizing turbojets, ramjets, and scramjets for cost-effective space access [89]. Advanced rocket propellants are being developed to enhance performance, reduce costs, and ensure environmental friendliness and safety [90]. Machine learning techniques are being applied to propulsion systems, including rockets, to improve performance and gain insights into complex propulsive flows [28]. Hybrid rocket propulsion is gaining traction for various applications like space tourism, satellite maneuvering, and planetary landers due to its safety, regenerative braking capabilities, and non-toxic propellants [16].

These advancements collectively shape the present and future landscape of rocket propulsion systems. Innovative structures enhance the reliability and performance of rocket propulsion systems. The topic of liquid and solid propellant rocket engine monitoring systems was covered [91]. Increased thrust, specific impulse, and constant burning rate provide enhanced propulsion [92]. Propeller weight and booster additions increased the performance of heavy-lift space launch vehicles. Patents and published articles demonstrate the advancements made in space propulsion systems [61]. Table 2 shows an overview of recent work on applications and future directions.

Table 2: An overview of recent work on applications and future directions.

SL	Year	Findings	Reference
1	2022	The study focuses on the efficiency of propulsion techniques under specific circumstances. Multistage rocket vehicles offer advantages and present prospects for improving engine technology.	[114]
2	2018	Mixtures of aluminum and water exhibit poor impulses and inefficient combustion. We have created theoretical models based on energy balance analysis.	[115]
3	2016	Burning solid fuel sources, with a focus on two-phase flows, turbulence, and radiative effects in motor interior ballistics.	[116]
4	2012	Benefits include less weight, lower costs, more dependability, and thermal stability. High-thrust engines can benefit from technology's scaling effects.	[117]
5	2006	We create liquid gelled and hypergolic bipropellants for LRE. The ISVE engine operates exceptionally well, thanks to effective combustion management.	[118]
6	2023	SiC/SiC ceramic matrix composite applications in liquid rocket engines can potentially improve engine efficiency. Potential future objectives include improving turbine temperatures to increase specific impulse and decrease propellant consumption.	[119]
7	2020	Future research in electric propulsion will focus on testing accuracy, predictive modeling, scalability, and performance realization for a variety of technologies in order to get around problems that can't be solved with focused studies and cutting-edge systems.	[120]

Current advancements in rocket propulsion systems for space exploration include the exploration of electric, laser, and nuclear rocket engines alongside traditional liquid, solid, and hybrid propellant systems [88, 93, 94]. Research is focused on developing more efficient and environmentally friendly propellants, such as "green propellants," to replace toxic options like ammonium perchlorate and hydrazine [95]. NASA is investigating continuous detonation cycle engines for interplanetary missions, aiming for improved performance and compact designs for missions to the Moon and Mars [96]. Additionally, Ariane Group has developed chemical propulsion systems for exploration missions to the Moon and Jupiter, addressing challenges like radiation protection and hydraulic system characterization. These advancements aim to enhance propulsion efficiency, safety, and versatility for future space exploration endeavors. Rocket propulsion systems offer peak efficiencies under specific conditions, considering factors like cost, payload, and thrust-to-weight ratio [97]. These systems typically involve combustion chambers, propellant injectors, and cooling mechanisms for optimal performance [7, 9, 10]. Rocket propulsion can vary based on propellant choices and operational modes, allowing for flexibility in design and application [98]. While rocket systems are ideal for launching from planetary surfaces due to their high energy requirements, advanced technologies like electric or solar-powered engines are being explored for future applications. In terms of efficiency and cost-effectiveness, rocket propulsion systems excel in providing high thrust levels for space travel but may face challenges related to propellant costs and environmental impact, making ongoing research crucial for enhancing overall performance and sustainability.

Future directions for rocket propulsion systems include advancements in reusable launch systems like SpaceX Falcon and Blue Origin New Shepherd [99], research on electric space thrusters to eliminate the need for neutralizers [27], and exploration of innovative propulsion systems such as steam rockets and ion-ion thrusters [18, 100]. These developments aim to enhance reliability, performance, and cost-effectiveness of launch vehicles, ultimately impacting space travel by enabling longer mission lifetimes, reduced weight, and lower propellant consumption [7]. Additionally, the focus on improving safety, efficiency, and environmental impact of propulsion systems is crucial for meeting mission requirements while minimizing negative effects on the environment. Overall, these advancements in rocket propulsion systems are poised to revolutionize space transport, making it more efficient, cost-effective, and sustainable for future space exploration endeavors.

7. Key innovations and their impact on space missions

Key innovations in rocket engine technology include novel contour geometries, advanced materials, and high-energy propellants like Ammonium Dinitramide (ADN) [60, 101]. These innovations have significant impacts on space missions by enhancing specific impulse, reducing environmental impact, and improving overall engine performance. Additionally, advancements in manufacturing techniques such as Direct Metal Laser Sintering (DMLS) are revolutionizing hardware production, leading to reduced costs and manufacturing times for components like the J-2X gas generator discharge duct [102]. These innovations collectively contribute to the development of high-performance, cost-effective rocket engines, enabling advancements in orbital propulsion, expander cycle engines, and classical gas generator engines [103]. The integration of these innovations into rocket propulsion systems is crucial for achieving higher thrust-to-weight ratios, increased reliability, and reduced launch costs, ultimately enhancing space exploration capabilities [104].

Key innovations in rocket engine technology that have significantly impacted space missions include novel contour geometries for thrust chambers, transpiration cooled thrust chambers made from ceramic matrix composites (CMC), additive manufacturing techniques for complex engine components, and the proposal of magnetic levitation and propulsion systems. These innovations offer advantages such as increased specific impulse, reduced stage weight, elimination of pressure loss from chamber cooling, and potential cost reductions. Additive manufacturing, specifically 3D printing, has shown promise in reducing costs and lead times associated with developing liquid rocket engine systems [105]. Table 3 shows an overview of recent work on key innovations and their impact on space missions.

Table 3: An overview of recent work on key innovations and their impact on space missions.

SL	Year	Findings	Reference
1	2022	Importance of nutrition in space missions for astronaut health. Development of technologies for long-duration space food sustainability.	[121]
2	2023	Hybrid rocket engines have potential in space applications. Technical challenges and solutions for hybrid propulsion are discussed.	[122]
3	2016	Recent advances in space launch vehicle technologies. Emphasis on electric pump cycle engine for small launch vehicle.	[123]
4	2010	AMBR engine increases payload gains and reduces manufacturing costs. Technologies developed show mission benefits and are ready for flight.	[124]
5	2009	Proposes magnetic levitation for future space vehicles. VML system cost-effective alternative to current rocket systems.	[125]
6	2017	International shifts are driving the development of methane engines. The best next-generation propellant for space travel is oxygen or methane.	[126]
7	2014	Challenges include high-power electric propulsion and cryogenic storage. The primary areas of focus are deep space exploration, propulsion technologies, and industrial capability.	[127]

Additionally, the use of CMC thrust chambers and advanced design approaches promise enhanced engine efficiency, reliability, and cost-effectiveness, making high-performance rocket engines more attractive for both governmental and private commercial space transportation [101]. The incorporation of additive manufacturing techniques in injector and thrust chamber devices allows for more efficient engine operation and complex geometries, further enhancing rocket engine performance [106]. Lastly, the proposal of magnetic levitation and propulsion systems as a greener alternative for future space vehicles aims to provide adequate thrust with lower long-term costs [107].

Advancements in rocket engine design, particularly through additive manufacturing (AM) techniques, have significantly impacted the efficiency and cost-effectiveness of space missions [108]. Companies like Relativity Space, SpaceX, Rocket Lab, and Blue Origin are leveraging AM for rocket engine production, enhancing cost and lead-time benefits. Additionally, developments in transpiration cooled thrust chambers using ceramic matrix composites promise increased specific impulse and engine life [109]. Furthermore, innovative concepts like the Laser Kinetic Energy Transfer (LKET) propulsion system offer a simple and cost-effective method to boost engine efficiency and thrust, potentially revolutionizing rocket propulsion [101]. These advancements not only improve mission performance but also hold the potential to reduce costs and enhance the overall viability of space exploration endeavors.

Emerging trends in rocket engine technology include the adoption of additive manufacturing for key components like valve housings [110], the development of air-breathing magneto plasma dynamic thrusters for potential atmospheric use [111], and the advancement of transpiration cooled thrust chambers made from ceramic matrix composites, promising increased efficiency and cost reduction [101]. Additionally, the shift towards methane engines due to their efficiency, lower cost, and eco-friendliness, especially for long-range space exploration plans, is a notable breakthrough [112]. Furthermore, innovative rocket engine designs based on mathematical models of space and particles are being explored, introducing new classifications of rocket engines and potential advancements in spacecraft velocities and energy efficiency [113]. These trends collectively have the potential to revolutionize future space missions by enhancing performance, reducing costs, and enabling new capabilities.

Conclusion

In conclusion, the recent advancements in propulsion systems for rocket engines represent a transformative leap forward in our ability to explore and utilize space. From the emergence of electric propulsion systems to the refinement of traditional chemical engines and the pursuit of reusable rocket technologies, these developments

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have not only enhanced the efficiency and reliability of space missions but have also opened up new frontiers for scientific research, commercial activities, and human exploration. The applications of these propulsion systems span a wide range of endeavors, from satellite deployment and deep space exploration to lunar missions and beyond. With each innovation, we move closer to realizing ambitious goals such as crewed missions to Mars, sustainable lunar habitats, and the commercialization of space. Moreover, these advancements have the potential to revolutionize industries on Earth, from telecommunications to transportation and resource extraction. As we continue to push the boundaries of space exploration, the importance of further research and development in propulsion systems cannot be overstated. Challenges such as increasing efficiency, reducing costs, and minimizing environmental impact remain paramount. However, with collaboration between academia, industry, and government agencies, we are poised to overcome these challenges and unlock the full potential of propulsion technologies, ushering in a new era of space exploration and utilization for the benefit of all humankind.

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