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A systematic approach to evaluating propulsion options for long-duration missions to Mars

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Abstract

Propulsion systems and launch mechanisms are analyzed to select the optimal rocket design for space travel to Mars. The advantages and disadvantages of various propulsion systems are described. A Pugh matrix is used to determine the optimum propulsion system and launch mechanism based; in part; on past performance characteristics. This paper recommends that an electrothermal propulsion system with a multistage launch mechanism be used for missions to Mars.

Keywords

Propulsion systems, Launch mechanisms, Mars, Pugh matrix, Electrothermal propulsion system

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Introduction

Other than Mars being Earth's adjacent planet in the solar system, there are many reasons to visit the "Red Planet". From science fiction geeks to conspiracy theorists, humans have long wondered what happens on Mars and believe that it is an important planet to explore. Recently, many astrobiologists have hypothesized and confirmed that Mars once had liquid water flowing throughout, nutrients to supply life, and a magnetic field similar to Earth's atmosphere, which may be conducive to life (1). Additionally, many geologists and scientists are puzzled about the planet's evolution and its surface, which for decades has kept scientists investigating whether there has ever been life on Mars. Lastly, Mars is considered very important stepping stone for future exploration of other planets and stars within the solar system. Martian rovers like the Sojourner, Opportunity, Spirit, Curiosity, and Perseverance have collected samples of rock and soil, which have revealed key details about its formation and evolution. The newest rover on Mars, Perseverance, has important instruments on board such as MOXIE (which produces oxygen from the Martian atmosphere), RIMFAX (analyzes the geological structure of the planet's subsurface), and SHERLOC (detects organic compounds) (2).

Reaching Mars requires a rocket, which in turn requires a propulsion system for transporting humans and resources from the surface of Earth to Mars. A propulsion system can either be an air-breathing system, which requires oxygen to allow for combustion, or a non-air-breathing system, which carries its own supply of oxygen. Rockets that leave the Earth's atmosphere use a non-air breathing system because there is no oxygen in the vacuum of space. A rocket has four forces acting on it during its flight: gravity, thrust, drag, and lift. These are the most important forces to analyze when creating the optimal design for a Martian rocket mission.

Chemical propulsion system

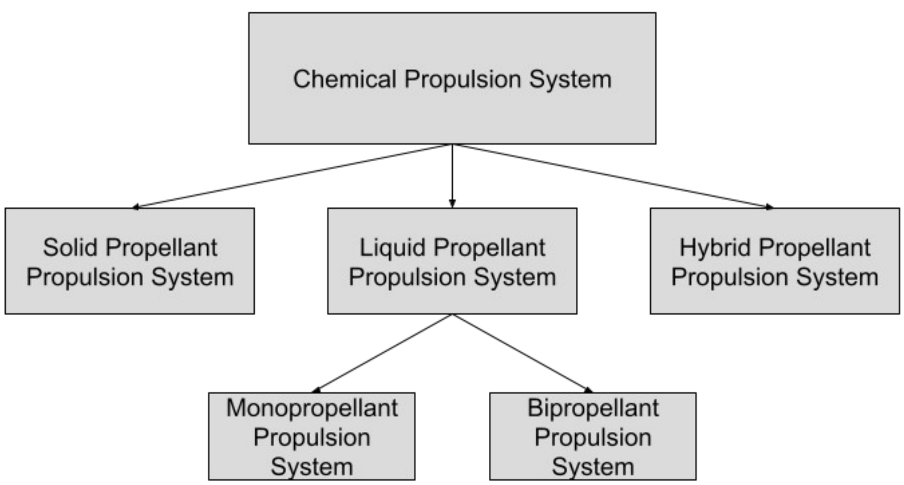

Figure 1. Chemical propulsion system

Solid propellant propulsion system

In a solid propellant propulsion system, the propellant comprises a mixture of fuel and oxidizer in solid form. This simplifies rocket design and makes it more stable without compromising consistent performance across ignition systems. However, this propulsion system does not have the capability for intermittent fuel burn, instead causing the propellant to continuously burn until all the fuel is exhausted through the nozzle. Solid rocket propulsion systems are considered to be less efficient than hybrid or liquid engines (3). However, they have their own share of advantages. They are more compact and smaller in comparison to traditional liquid rockets. This allows for more cargo carrying capacity. Moreover, solid propulsion systems have a high thrust - to - weight ratio, which allows for a greater acceleration than other types of propulsion systems.

This Thrust to Weight Ratio is given by,

$$\text{Ratio} = \frac{F}{w} = \frac{Thrust}{Weight} = \frac{mass \cdot acceleration}{mass \cdot gravitationalacceleration} = \frac{acceleration}{gravitationalaccerlation} \quad \text{Equation 1}$$

The gravitational acceleration is a constant with a value of $9.8\frac{m}{s^2}$

Since the gravitational acceleration is a constant, the faster the acceleration of the rocket, the greater the thrust-to-weight ratio. Additionally, the thrust to weight ratio must be >1 for the rocket to accelerate upward. However, solid propulsion systems have a relatively low specific impulse compared to liquid propulsion systems. Since solid propulsion system burn their propellant at a predictive rate, scientists can more easily calculate the amount of fuel required to reach the rocket's desired location in space.

Liquid propellant propulsion system

The second type of chemical propulsion system is the liquid propulsion system, which is the most efficient and provides a high level of control. Many NASA missions, such as the Apollo Program, Space Shuttle, and the Chandra X-ray Observatory have utilized this type of propulsion system (4). A liquid propulsion system works by converting the liquid into a gaseous state, which is later discharged from the engines to create thrust. The liquid propulsion system is classified as either a monopropellant system or a bipropellant system. A monopropellant system contains a mixture of an oxidizer and a combustible matter. The monopropellant must go through a catalytic chamber in which hot gases are created as a byproduct of its decomposition. These hot gases then travel through the exhaust nozzle to create thrust. A monopropellant engine has a simple design and is reliable. However, it achieves a low specific impulse and thrust due to many issues within the catalyst chamber in the rocket (5). In a bipropellant system, the fuel and oxidizer are two separate liquids. These two liquids then travel to the combustion chamber in which the pressure increases. This allows for the combustion to shoot out of the exhaust. A bipropellant has many differences when compared to a monopropellant. A bipropellant propulsion system is more efficient and has a higher exhaust velocity in comparison to a solid or hybrid rocket. However, bipropellant liquid propulsion systems have multiple failure points and require a large capital expenditure to design, test, and build.

Hybrid propellant propulsion system

In a hybrid rocket engine, the propellant is a mixture of both liquid and solid phases. In all chemical propulsion systems, a propellant is the combination of fuel and an oxidizer. In many cases, the oxidizer takes the liquid form, and the fuel takes the solid form. An oxidizer is a chemical required in propulsion systems that burns the propellant and the most common fuels used in rockets are liquid hydrogen, liquid methane, kerosene, and hydrazine (6). The hybrid propulsion system is considered to be simpler, less expensive, and safer than the liquid propellant system (7). However, it is difficult to refuel the solid fuel. Furthermore, the ratio of the oxidizer to fuel may alter the efficiency of the rocket's propulsion.

Nuclear Propulsion System

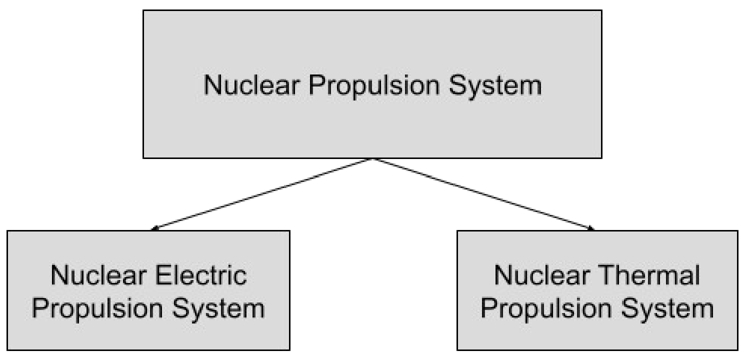

Figure 2. Nuclear Propulsion System

The nuclear propulsion system for spacecrafts is a theory that was created half a century ago. However, rockets with a nuclear propulsion system have not been developed because of the high risk of radioactive debris spreading in the event of an accident. Nuclear rocket engines either use a solid core system or a fluid core system. The solid core system is very similar to the traditional liquid propulsion system; the only difference is that the combustion chamber has been replaced by a reactor (8). The nuclear electric propulsion system generates electricity through a nuclear reactor and transfers it to electric thrusters to create an exhaust velocity (9). A nuclear thermal propulsion system is considered to have a high exhaust velocity and a high specific impulse (10). The reason scientists and engineers have investigated the possibility of a nuclear propulsion system is due to its high thrust and high specific impulse, which can increase interplanetary trips while decreasing the duration of each trip.

Electric propulsion system

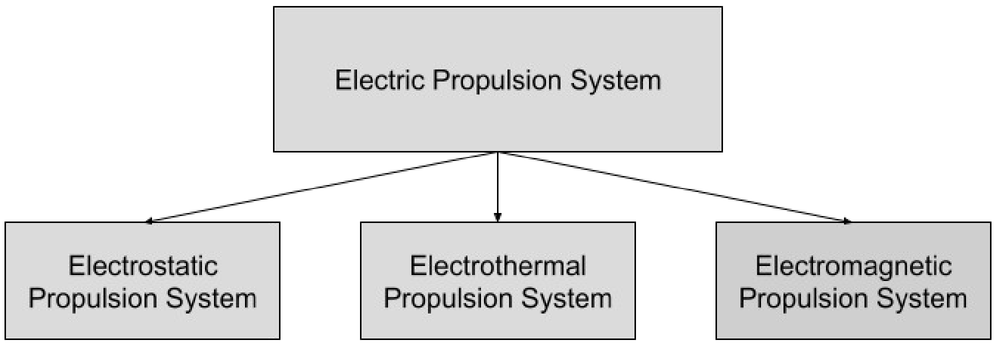

Figure 3. Electric Propulsion System

The electric propulsion system is a popular technology used on rockets and satellites due to its high specific impulse and its ability to carry less propellant compared to chemical propulsion systems (11). However, the main disadvantage of an electric propulsion system is that it is unsuitable for launches from the Earth's surface (due to its small thrust). There are three main types of electric propulsion systems: electrostatic, electrothermal, and electromagnetic. Each type uses a different energy source to accelerate plasma ions (12). Due to the use of electrical power to accelerate a rocket, the distance that an electric propulsion rocket travels is much further than chemical propulsion systems that use the same amount of propellant. The reason behind this is due to its unique way of creating thrust. Certain propulsion systems emit heavy gases like xenon to create thrust. For example, the Dawn spacecraft, which used an ion propulsion system, continued to accelerate for 11 years before running out of fuel (13). Ion propulsion systems are being considered by companies such as NASA and SpaceX. An ion thruster is a type of electric propulsion system that is currently being used by NASA to maintain geosynchronous Earth orbit communication satellites in their chosen locations.

Rocket Launch Mechanisms

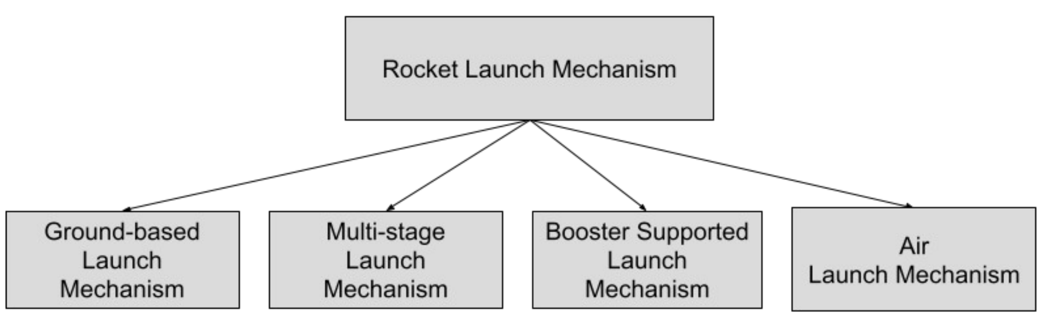

Figure 4: Rocket Launch Mechanism

To find the best rocket design for the mission to Mars, the first 8 1/2 minutes of the launch must be analyzed, which is the time it takes for the rocket to leave the Earth's atmosphere from ground level (14). For a rocket to exit the Earth's atmosphere, it must be assisted by a launch mechanism. There are four main launch mechanisms: ground-based, multistage, booster-supported, and air launch. The ground-based launch system, as the names describes, is a type of launch that truly takes place from the surface of the Earth. In this system, an external force is applied to the rocket to allow for greater initial acceleration and propellant conservation. In a multistage launch system, the rocket has numerous stages in which each engine carries its own propellant. This is a brute force technique that allows the rocket to leave the Earth's atmosphere, as the rockets are stacked upon each other, in which one rocket ignites after another. It is considered to be the most modern mechanism and has been used on recent SpaceX flights such as the Falcon 9 rocket (15). In a booster-supported launch mechanism, the rocket ascends through staging, in which the two stages are either on top of each other (serial staging) or side by side (parallel staging). An example of serial staging is the Saturn V rocket, and an example of parallel staging is the Space Shuttle. In an air launch mechanism, a secondary aircraft travels to the low-level orbit section of the atmosphere with the rocket attached to it. When it reaches the desired height, the rocket dislodges from the aircraft and leaves the atmosphere. This method allows for a decrease in the amount of rocket propellant utilized because the aircraft spends its fuel to carry the rocket close to the edge of the atmosphere.

Methods

Design Criteria Terms	**Description**
Specific Impulse	The specific impulse measures the efficiency of a propulsion system's thrust.
Exhaust Velocity	The exhaust velocity refers to the velocity at which the exhaust gases leave the rocket engine's nozzle.
Availability of Technology	The availability of technology simply refers to whether the technology is currently usable and can function as designed.
Thrust Coefficient	The thrust coefficient is the thrust per unit chamber pressure. It is used to determine how much the nozzle helps increase the thrust of the rocket.
Mass	The mass of the propulsion system.
Complexity	The level of complexity refers to whether the system can be built using currently available technology and/or tools.
Total Cost	The cost of the assembly and materials for the propulsion system.

Figure 5. The associated description of the design criteria terms.

All the design criteria were equally weighted except for availability of technology. The optimum propulsion system has already been developed and tested, therefore, the availability of technology was given the most importance. As this study was looking for current solutions, any propulsion systems that have not been thoroughly tested were not considered to be strong choices for missions to Mars. The primary reasons behind this are due to concerns regarding the safety of the crew and for the likelihood of the mission being a success.

Design Criteria	DATUM: Liquid Propellant Propulsion System	Design 1: Solid Propellant Propulsion System	Design 2: Hybrid Propellant Chemical Propulsion System	Design 3: Nuclear Thermal Propulsion System	Design 4: Nuclear Electric Propulsion System	Design 5: Electrostatic Propulsion System	Design 6: Electro magnetic Propulsion System	Design 7: Electrothermal Propulsion System
Specific Impulse	0	-	0	+	+	+	+	+
Exhaust Velocity	0	0	0	+	+	+	+	+
Availability of Technology	0	+	+	-	-	-	-	+
Thrust Coefficient	0	0	0	+	+	-	-	-
Mass	0	-	-	-	-	+	+	+
Complexity	0	+	-	-	-	-	-	-
Total Cost	0	+	+	-	-	-	-	-
+	0	3	2	3	3	3	3	4
0	7	2	3	0	0	0	0	0
-	0	2	2	4	4	4	4	3
Total Points	0	1	0	-1	-1	-1	-1	1

Figure 6. Pugh matrix for the design criteria used to analyze the propulsion system.

In Figure 6, positive, zero, and negative signs are used to describe the differences between the propulsion system designs and datum. The negative sign for mass means that the propulsion system weighs more while the positive sign for mass means that the propulsion system weighs less. These indicators were used because lighter propulsion systems are advantageous for rockets. The same is the case with the complexity criterion, in which the negative sign indicates a more difficult build, while the positive sign indicates an easier build. The complexity factor was graded as such because it is better to have a propulsion system that easier to build. Total cost is similar to the two previous criteria, as it is better for a propulsion system to cost less than the datum. Therefore, the positive sign is used to show that the propulsion system costs less, while the negative sign indicates that it costs more than the datum.

To ascertain which propulsion system is best based on certain characteristics, the Pugh Matrix was used (Figure 6). This revealed that the best propulsion system for traveling to Mars is either the Solid propellant propulsion system or the electrothermal propulsion system, both of which tied for the highest score. First, the specific impulse of the electrothermal propulsion system is greater than that of the solid propulsion system. As stated earlier, electric propulsion systems have the highest specific impulse in current engines. Second, the exhaust velocity of the electrothermal propulsion system is higher than that of the solid propulsion system. The electrothermal propulsion system is known as an intense form for accelerating propellant. It is better than all current chemical propulsion systems as they create thrust by expanding chamber- heated propellant gases through the exhaust nozzle. Next, the thrust coefficient of the solid propulsion system is greater than that of the electrothermal propulsion system. This is common for most chemical propulsion systems because their combustion method uses an oxidizer and a propellant. Furthermore, the solid propulsion system has a simpler manufacturing process and a lesser cost than that of an electrothermal propulsion system. Though it is important for propulsion systems to have a lower total cost, due to the historic mission that this rocket will debut on, it would probably have no shortage of funds to successfully achieve the mission. One of the greatest advantages that the electrothermal propulsion system has its low overall mass, which allows for more resources, such as technologies and materials, to be allocated for artificial Mars habitats.

Launch Mechanism	**Choices for Ground-Based**	**Choices for Multistage**	**Choices for Booster-supported**	**Choices for Air Launch**
Chemical Propulsion System	Solid Propellant Liquid Propellant Hybrid Propellant	Solid Propellant Liquid Propellant Hybrid Propellant	Solid Propellant Liquid Propellant Hybrid Propellant	Solid Propellant Liquid Propellant Hybrid Propellant
Electric Propulsion System	None	Electrostatic Electrothermal Electromagnetic	Electrostatic Electrostatic Electromagnetic	None
Nuclear Propulsion System	None	Nuclear Electric Nuclear Thermal	Nuclear Electric Nuclear Thermal	None

Figure 7. This morphological matrix shows the propulsion system options for each launch mechanism.

This matrix shows the different variations of propulsion systems and launch mechanisms to choose in order to find the optimal spacecraft to travel to Mars. There are two components in this matrix: propulsion systems and launch mechanism. There are eight options for the propulsion system and four options for the launch system. While Figure 7 shows that ground-based and air launch mechanisms cannot be used for electric propulsion systems and nuclear propulsion systems, the reasons as to why are not the same. Electric propulsion systems cannot create a weight-to-thrust ratio of >1 Newton resulting in insufficient vertical acceleration to leave the Earth's atmosphere. Nuclear propulsion systems are considered unsafe for two reasons: their source of energy is volatile, and the propulsion system not having had enough testing. On the other hand, chemical propulsion systems can use any of the four launch mechanisms since the exhaust velocity from their combustion is greater than $9.81\frac{m}{s^2}$, Earth's gravitational acceleration, and they are considered the safest option for rockets.

Results

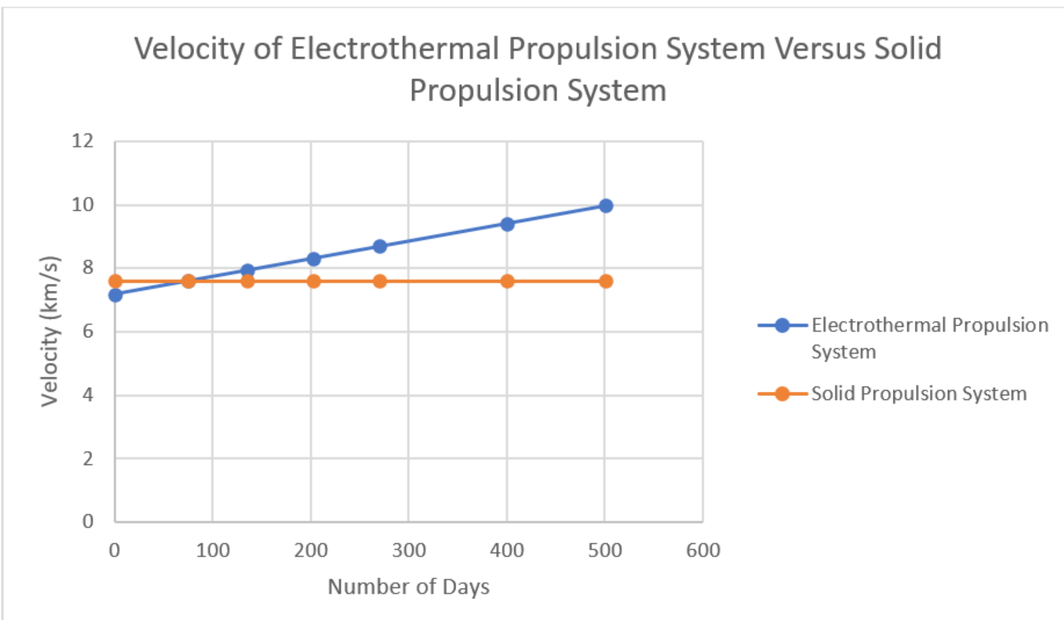

Figure 8. The velocity of the electrothermal propulsion system versus that of the solid propulsion system.

After finding the initial velocity of both the electrothermal propulsion system and the solid propulsion system, the velocity was calculated using the following equation for kinematic velocity.

$$v = at + v_0 \quad \text{Equation 2}$$

The initial velocity of the solid propulsion system was $11.176\frac{km}{S}$. Since the rocket with the solid propulsion system would coast the distance till Mars after it left the Earth's atmosphere, this propulsion system's acceleration would be $0\frac{m}{s^2}$. Next, the equation of the electrothermal propulsion system must be calculated. The initial velocity of this system would be the same as the speed of the International Space Station at $7.17\frac{km}{s}$. The acceleration of the electrothermal propulsion system is $0.000000065\frac{km}{S^2}$ (16). The variable t, in Equation 1 stand for time in days. Therefore, to find the velocity at a certain day, the values for acceleration, initial velocity, and that exact mission day were substituted for the corresponding variables in the equation.

After finding the velocity for both propulsions systems, the equation, $y=mx+b$ was solved. Note that $v=at\cdot v_0$ is the slope intercept form rewritten. The equation of the solid propulsion system is $v=11.176\frac{km}{s}$ since the acceleration is $0\frac{km}{s^2}$. This is true since acceleration is the slope in the velocity equation. To find the equation of the electrothermal propulsion system, the values of acceleration and initial velocity were substituted; the equation is $v=\left(0.000000065\frac{km}{s^2}\right)t+7.17\frac{km}{s}$ in which t is time in seconds. In order to find the velocity on a certain day, the following equation was used: $v=\left(86400\left(\left(0.000000065\frac{km}{s^2}\right)t\right)\right)+7.17\frac{km}{s}$, where t is the number of days.

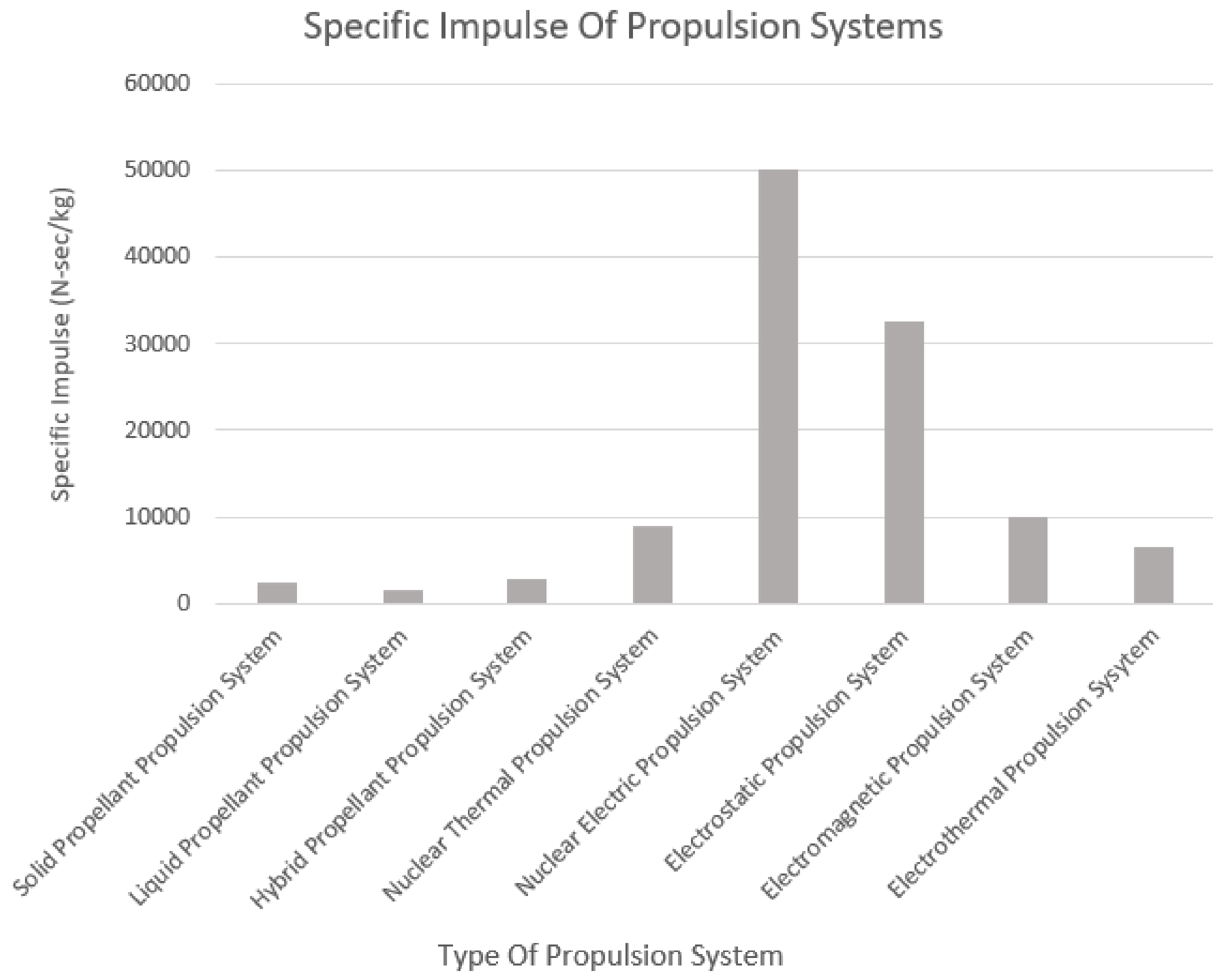

Figure 9. The specific impulse for the propulsion systems: Solid Propellant Propulsion System (17.), Liquid Propellant Propulsion System (18), Hybrid Propellant Propulsion System (18), Nuclear Thermal Propulsion System (19), Nuclear Electric Propulsion System (20), Electrostatic Propulsion System (21), Electromagnetic Propulsion System (22), Electrothermal Propulsion System (21).

The bar chart shows the specific impulse of each type of propulsion system to visually represent the differences among specific impulses of propulsion systems. The highest specific impulse is obtained using the nuclear electric propulsion system while the lowest is with the liquid propellant propulsion system. From the chart, it can be established that chemical propulsion systems have the lowest specific impulse among all the propulsion systems.

Discussion

While both the electrothermal and solid propulsion systems seem equally capable of being utilized for traveling to Mars (based on them receiving the same scores on the Pugh Matrix), the resources and cost required for both propulsion systems to function must be considered. Since the solid propulsion system is categorized under chemical propulsion systems, it would have to carry its own fuel and oxidizer. As seen in Figure 8, an electrothermal propulsion system can exceed the velocity of the solid propulsion system. Since electrothermal propulsion systems receive their energy from the sun, the amount of propellant required for them to have the same velocity as traditional propulsion systems decreases. This in turn allows for a reduction in propellant mass, which effectively lowers the costs of the mission. Additionally, the time it takes for the rocket to travel to Mars is an important factor, as time is equal to carrying capacity on the spacecraft. The longer the spacecraft takes to travel to Mars, the more supplies will be required for the journey of the astronauts and not for the actual mission while on the planet. Hence, the relative velocities of the electrothermal and solid propulsion systems must be a consideration. At the point when the rocket equipped with an electrothermal propulsion system leaves the atmosphere it travels at 7.17 km/s while the velocity of the rocket with a solid propulsion system is 7.59 km/s. The journey to Mars would take approximately nine months (23). According to this estimate, Figure 8 shows that the electrothermal propulsion system will still have a faster velocity than the solid propulsion system at 270 days. Therefore, the time required for an electrothermal propulsion system to finish a journey to Mars would be shorter than the time required if powered by a solid propulsion system.

While the author believes that using an electrothermal propulsion system would be optimal, NASA advocates for a nuclear thermal propulsion system (24). Both propulsion systems are optimal for a mission to Mars as they work with different time frames for the mission. This research paper investigates which propulsion system would be best if a rocket to Mars were to launch today. On the other hand, NASA has planned for a launch in the 2030s (25). This paper discusses current propulsion systems to be used for the Mars mission while NASA is looking at future technologies for spacecraft propulsion.

Conclusion

The two propulsion systems with the highest score were the solid propulsion system and the electrothermal propulsion system. While the solid propulsion system has a higher thrust-to-weight ratio the electrothermal propulsion system has a greater specific impulse, a lower mass, and can reach Mars faster. Subsequently, a multistage launch mechanism is the most preferred type of launch vehicle as it allows for an efficient acceleration of the rocket's altitude and height while conserving rocket propellent. After assessing the data, the recommendation of this paper is that a multi-stage launch mechanism with an electrothermal propulsion system should be used for the Mars mission.

Limitations

This paper had two main limitations regarding its data. The first limitation was that the data collection process was inefficient. Due to the lack of quantitative data available on the internet, more than half the time that went into this study was to find data that could be analyzed to show differences in the types of propulsion systems. The second limitation of this paper was the recency of the data. The data that was collected was from the 1990's to 2021. Hence, although the data researched was useful, comparison was difficult due to different (non-standardized) experimental conditions and varying accuracy of data processing instruments.

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