New Zealand's Next Top Engineering Scientist

How much fuel is required for a manned mission to Mars

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Summery

This report is an investigation into the amount of fuel that would be required for a manned mission to mars. This means we need fuel to travel to mars then fuel to make it back. Time is critical in this as the rocket and mars must meet in the same place at the same time. We calculated the amount of fuel required be basing a rocket on the fuel consumption of a current space shuttle leaving orbit. The two main areas of fuel consumption are leaving earths orbit and mars's orbit. We calculated the fuel consumption from these two areas to be 152800kg. This is based on the weight of the rocket and the thrust which is needed.

Introduction

This is an investigation into how much fuel is required for a manned mission to Mars. The rocket must have enough fuel to travel to Mars and back. Each way involves three main sections of fuel usage.

- Escaping the planet's gravity
- Travelling through space between the planets gravitational fields
- Entering an atmosphere.

The bulk of the fuel will be spent on providing the thrust to escape a planet's gravity. We will assume no fuel is used during travel through space since there are no forces to be overcome. Re-entry into a planets atmosphere will also use little fuel if the friction force to decelerate the rocket is maximised through the surface area of the rocket and the angle of entry.

Escaping the planet's gravity

In order to escape Earth's gravity, the weight force of the rocket must be opposed with thrust. The thrust must be greater than weight force in order to produce a net force upwards.

The minimum velocity which must be attained in order to escape a planet's gravitational can be modelled by the following equation:

$$\frac{1}{2}mv^2 = \frac{GMm}{r} \quad (1)$$

$$v^2 = \frac{2GM}{r}$$

$$Ve = \sqrt{\frac{2GM}{r}}$$

- Where G is a constant and equals 6.67×10^{-11}
- M is the mass of the planet
- r is the radius of the planet

$$Ve = \sqrt{\frac{2 \times 6.67 \times 10^{-11} \times 5.97 \times 10^{24}}{6.38 \times 10^{6}}}$$

$$Ve = 11.16\ kms^{-1}$$

In order to escape Earths gravitational field a rocket must reach an exit speed of above $11.16 kms^{-1}$. Similarly, the exit velocity of Mars's gravitational field is over $5.0 kms^{-1}$.

Using laws of accelerated motion formula, we can then work out the minimum acceleration of the rocket in order to escape earth's gravity. The exit velocity must be attained at a distance above the earth of 30000km.

(1) Smaill, Chris. Cox, Anna. (1995). Continuing Physics. Auckland: Pearson

$$Ve^2 - Vi^2 = 2ad$$

$$11160^2 - 0^2 = 2a(35786000)$$

$$124545600 = 71572000a$$

$$a = \frac{124545600}{71572000}$$

$$a = 1.74ms^{-2}$$

The rocket must therefore have an average, upward acceleration of 1.74ms^{-2}.

Newton's second law states that the net force on any object is equal to its mass multiplied by its acceleration. The Thrust provided by the rocket less its weight due to gravity will be the net force.

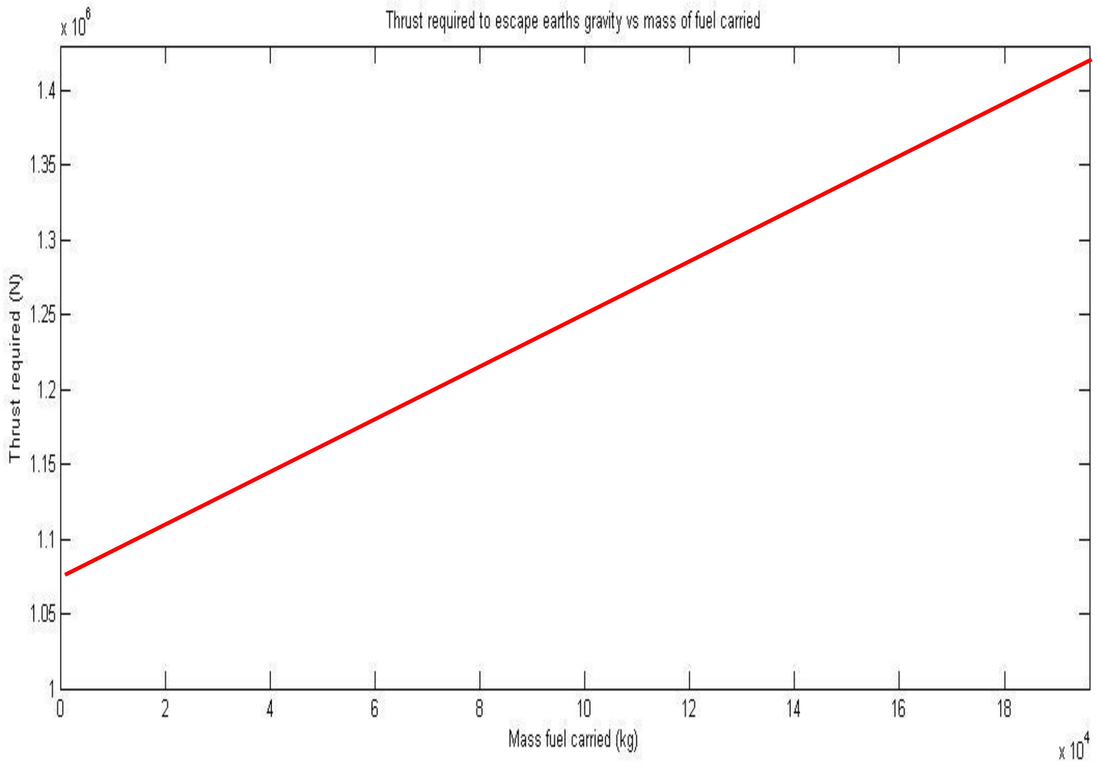
$$Thrust - weight = ma$$

$$Thrust - weight = (mass(rocket) + mass(fuel)) \times 1.74$$

Based on a Space Shuttle including all of its boosters. [(2)(3)]

$$Thrust - 109000 \times 9.81 = (10900 + mass(fuel)) \times 1.74$$

$$Thrust = 1088256 + 1.74(mass\ of\ fuel)$$



(2) www.nasa.gov/worldbook/rocket_worldbook.html
(3) http://wiki.answers.com/Q?what_is_the_weight_of_a_space_shuttle

This graph shows how the thrust required to escape the Earths atmosphere increases as the amount of fuel carried is increased. More fuel will be required to travel to Mars but the thrust must be increased in doing so.

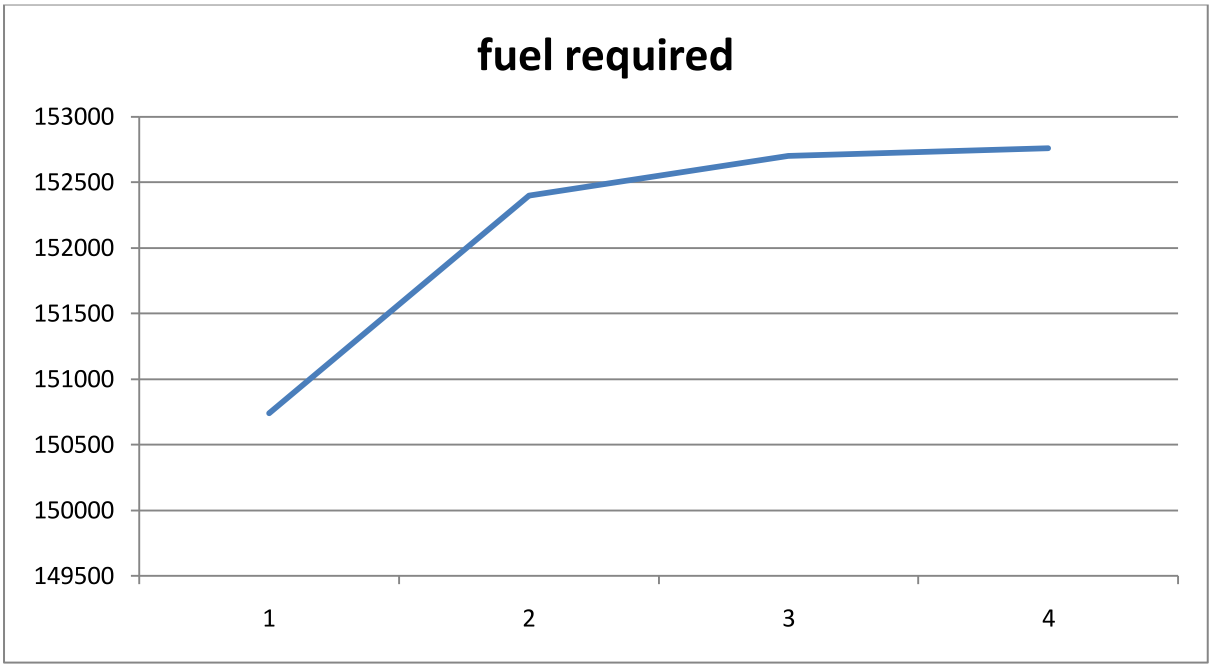
A space shuttle uses approximately 98100kg of fuel to escape the Earths gravity. To escape Mars's gravity, will require less fuel since the gravitational field is weaker. If we assume the masses of the rocket and fuel during takeoff from earth and mars to be equal at this point, we can say that the fuel used will be proportional to the fuel required to escape earths gravity, multiplied by escape velocity of mars divided by the escape velocity of earth.

ie fuel used during takeoff from mars equals 98100x(5/11.16) = 44000kg

This means with these assumptions the rocket will need 98100+44000 = 142100kg of fuel, however this is incorrect. The mass of the rocket escaping earth will be significantly greater than the mass of the rocket escaping mars.

When the rocket is escaping earth with this much weight, it will require more thrust, which will require more fuel which adds more weight and so on.

Thrust		% increase in thrust		Fuel required
1088256+1.74(98100)	=1258950			
1088256+1.74(142100)	=1335510	1.068	1.068x142100	=150739.68
1088256+1.74(150739.68)	=1350543.043	1.011	1.011x150739.68	=152397.8165
1088256+1.74(152397.8165)	=1353428.201	1.002	1.002x152397.8165	=152702.6121
1088256+1.74(152702.6121)	=1353958.545	1.000392	1.000392x152702.6121	=152762.449



The graph will continue to level out indefinitely. As more fuel is added, more fuel must be added to compensate for the increase in weight. This addition of fuel as decreased through each cycle because of the constant mass of the rocket with no fuel.

With this model we can estimate the fuel required for a return trip to Mars is approximately 152800kg.

Assumptions

We have assumed that the proposed rocket to be flown to Mars, achieves the same amount of thrust per unit of fuel, and uses the same type of fuel, that a space shuttle uses to reach orbit.

Limitations

This model is limited because it doesn't factor in an increase in weight of the rocket required if it is to have the capacity to hold larger volumes of fuel. 90% of a space shuttles weight is fuel. Therefore the extra weight of increasing the capacity of the fuel tanks will be less significant.

This model is also limited because it doesn't account for a decrease in weight during escape from Earth's gravity if any boosters are dropped.

Travelling Through Space between the gravitational fields

Space is most commonly referred to being a vacuum. This implies that no physical matter exists in free space. Using this assumption, a conclusion is made that any object travelling through space at a certain velocity will not decelerate on the basis of "air resistance." Since there are no particles present to provide an opposing force to the forward direction thrust of any object travelling through free space, there will result $0ms^{-1}$ deceleration. So theoretically, if a space shuttle accelerated to a certain velocity and it shut down its engines, it would maintain this velocity for the rest of its journey until any backward-thrust is generated by the engines to slow down the space shuttle.

So once the space shuttle has broken out of the orbit of the planet and accelerated to an appropriate velocity, it will shut down its propellant engines and stop consuming any more fuel. The engines will be shut down until the planet is reached.

This will be the case both ways of the journey, going to Mars from Earth and coming back from Mars to Earth.

Assumptions and Limitations

The main assumption made for the idea of travelling in free space is that the resistant force will be zero; hence, there will be no extra fuel consumption.

But this does not take into account solar winds, presence of very small amounts of isolated matter or space debris, etc, that will definitely slow down the shuttle moving through free space. This is because it will provide a resistant force in the opposite direction, hence, decreasing the net force in the forward direction. So if the current velocity was to be corrected to the original velocity, fuel has to be used up to provide acceleration to reach the greater velocity.

Entry into Mar's Atmosphere

The closest reports to entry into Mar's atmosphere are the reports carried out by space organizations after successful re-entries into the Earth's atmosphere. One such report has been released by NASA going on about Optimum Re-entry Corridors. But Jim McLane's proposal includes a couple of major caveats: the trip to Mars should be one-way, and have a crew of only one person.

Source: Universe Today, http//www.universetoday.com/13037/a-1-way-1-person-mission-to-mars/

Optimization of Fuel Efficiency: The thickness of the atmosphere is constantly changing, it is in a state of flux. It varies due to the behavior of the sun and different weather phenomena. When there is increased solar activity, such as the eruption of solar flares were they send out streams of energetic particles that collide with the magnetic field of the Earth and cause the atmosphere to expand. Also active weather patterns and environmental conditions, changes also cause the atmosphere to expand. The height of the atmosphere is also dependent on where you are located on earth. Along the equator, the atmosphere sticks out more so than the poles due to the centrifugal effect created by the Earth rotating on its axis and the gravitational attraction of the Moon. So in theory to reduce the amount of fuel or help conserve the amount of fuel needed to get into the atmosphere it would be best to launch during a time of little or no solar activity or climate and environmental changes and to launch from either of the poles so that the atmosphere distance is minimized the best it can.

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Another way to optimize fuel is to launch the shuttle so that it reaches Mars at the minimum distance possible. Mars and Earth travel in elliptical paths about the sun. So the distance between Mars and Earth varies from being as close as 33,900,000 miles (54,500,000 kilometers) to as far as about 249,000,000 miles (401,300,000 kilometers). Below is a list of dates that in the past and predicted future distances that the Earth and Mars are less than 56,000,000km apart.

date	Earth-Mars distance (ua)	(Mkm)
25 august 1719	0.374010	55.951
13 august 1766	0.373260	55.839
18 august 1845	0.373021	55.803
22 august 1924	0.372846	55.777
27 august 2003	0.372719	55.758
15 august 2050	0.374051	55.957
30 august 2082	0.373564	55.884
19 august 2129	0.373276	55.841
24 august 2208	0.372794	55.769
28 august 2287	0.372254	55.688

The time that is estimated for a manned space shuttle to reach Mars is 4-6months. So to minimize the distance needed to travel it is best to leave Earth 4-6 months before this time. From the table above the best time for a manned shuttle launch to Mars would be around February-April 2050. This would thus optimize the fuel by reducing the distance that the shuttle has to travel.

http://www.aerospaceweb.org/question/atmosphere/q0090.shtml

Landing on Mars: Getting to Mar's is one thing, ensuring you carry enough fuel is one thing. But landing on Mar's is another whole problem in itself. There has only been a 40% success rate in Missions that have landed the spacecrafts safely on Mars. All of these missions have been with light weight crafts carrying cameras and instruments used to get readings of the Martian environment. A manned mission would mean a heavy space shuttle would have to be employed. People presume that we would be able to land Mars easily because we have landed on the moon and successfully re-entered earth's atmosphere numerous times. But due to Mar's atmosphere it would be made extremely difficult. The spacecraft would be too heavy to land the way it would on the Moon due to the amount of atmosphere using propulsive technology completely. There's too little atmosphere to land the way we do on Earth by using parachutes, airbags or thrusters. These won't work by themselves or in combination. So until a new system has been formed that is well suited to the gravity of 3.72ms-2 of Mars. Then a manned mission to Mars would be out of the question due to the inability to land successfully.

http://www.universetoday.com/7024/the-mars-landing-approach-getting-large-payloads-to-the-surface-of-the-red-planet/

<u>Propulsion methods including exhaust velocity, thrust, firing duration, maximum velocity an how ready the method is.</u>

This table compares different methods of space propulsion. Our answer to the question is based on a hybrid rocket burning both solid fuel and liquid fuel in the form of liquid hydrogen and liquid oxygen.

Method	Effective Exhaust Velocity (km/s)	Thrust (N)	Firing Duration	Maximum Delta-v (km/s)	Technology readiness level
Solid-fuel rocket	1 – 4	10^3 - 10^7	minutes	~ 7	9:Flight proven
Hybrid rocket	1.5 - 4.2	<0.1 - 10^7	minutes	> 3	9:Flight proven
Liquid-fuel rocket	1 - 4.7	0.1 - 10^7	minutes	~ 9	9:Flight proven
Electrostatic ion thruster	15 – 210	10^{-3} - 10	months/years	> 100	9:Flight proven
Pulsed plasma thruster (PPT)	~ 20	~ 0.1	~2,000-10,000 hours	?	7:Prototype demoed in space
Solar sails	300,000:Light 145-750:Wind	9/km^2 @ 1 AU 230/km^2@0.2AU 10^{-10}/km^2@4 ly	indefinite	> 40	9:Light pressure attitude-control flight proven 6:Deploy-only demoed in space 5:Light-sail validated in lit vacuum
Nuclear thermal rocket	9	10^7	minutes	> ~ 20	6:Prototype demoed on ground

Source: http://en.wikipedia.org/wiki/Spacecraft_propulsion

The table shows a large range of methods which could also be considered for space travel to mars. Perhaps a method with a larger exhaust velocity will be more effective at reducing the time to mars, however the amount of fuel used would also be greater, making it difficult to escape a planets gravitational field.

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There are 4 main types of rocket propulsions which are available to use. These consist of solid fuel chemical propulsion, liquid fuel chemical propulsion, cold gas chemical propulsion and ion.

Type	Uses	Advantages	Disadvantages
Solid fuel chemical propulsion	main booster	simple, reliable, few moving parts, lots of thrust	not restartable
Liquid fuel chemical propulsion	main booster, small control	restartable, controllable, lots of thrust	complex
Cold-gas chemical propulsion	small control	restartable, controllable	low thrust
Ion	in space booster	restartable, controllable, high specific impulse	complex

Source: http://www.qrg.northwestern.edu/projects/vss/docs/propulsion/2-what-are-the-types-of-rocket-propulsion.html

The solid motors are manly used as booster rockets. This is because a large amount of thrust is able to be produced because it needs to provide enough fuel to feed the engines which provide enough lift for the rocket to escape gravity. However the disadvantage is it cannot be controlled or restarted so it is inappropriate in any other context. They are very reliable and have a high shelf life. We would need two of these one to get off earth and one to get off mars because as this cannot be controlled or restarted as once the solid begins burning.

The liquid motors can come in many shapes and sizes. Most of these are controllable whilst still being able to give a lot of thrust. They are controllable however they are complex. They can be broken into three main types; monopropellant, bipropellant, and cryogenic thrusters. *'Monopropellants only use one propellant such as hydrazine. Bipropellants use a fuel and an oxidizer such as RP-1 and* H_2O_2*. Cryogenic systems use liquefied gases such as LiH and LOX (liquid hydrogen and liquid oxygen).'* You would need the hydrogen and oxygen to be very cold to make them liquids. The liquids hydrogen and oxygen are modeled by the chemical equation: $2H_2 + 2O_2 \rightarrow 2H_2O_2$ + energy released. With each of these 3 steps the complexity increases but the performance increases to. This pushes the rocket to a higher altitude of around 185km.

Cold-gas motor has similar controllability to liquids but is not as complex and are lighter. The contents are under pressure inside and when the valve is opened the gas streams out. The thrust for this is quite low.

Ion engines are very different because they are low thrust engines which can run for long periods of time. The length of use is generally days to months were as the others are seconds to days.

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<u>There are consequences if a human is in space for a long period of time. An astronaut can spend an indefinite number of days in space if they minimize these consequences.</u>

Physiological consequences:

Earth has a gravity value of 9.81m/s^2. Mars however has a gravity value of 38% of this; 3.7278m/s^2. Due to this the muscles in a human's body would not need to work as hard on mars. In response to this the muscles begin to shrink as they are under loaded. An example of this includes your heart. It will be easier to pump the blood around your body which will endure your heart to get weaker.(4) This could mean if your muscles get too weak when you return to earth you will not be able to stand upright as your muscles will be very fragile. Astronauts who have spent 180days at space stations show a loss of more than 40% of their muscles work capacity.(4) The more toned a person is will not help; by the time they return they will have the muscle tonnage of about an 80year old man. As well as muscles, bones structures are affected. (5) Your bones are not needed as much and become brittle due to the loss of calcium.

There is a great threat to astronauts from rays. The most damaging of these rays is the "GCRs" (Galactic Cosmic Rays). "GCRs barrel through the skin of spaceships and people like tiny cannon balls, breaking the strands of DNA molecules, damaging genes and killing cells." There is a very rare chance however that an astronaut will experience a full dosage of these deep space rays. There is also the ultra violet radiation which will affect the astronauts and particle radiation.(7)

Another consequence is there are no resources available to you so you must bring all of them with you. You need enough food, water, clothes and medical supplies, not to mention fuel and shielding. For about six of you this is about 3million pounds (1360777.1 kgs). This is where the problem lies because the shuttle can lift about 50,000 pounds (22679.618 kgs). So it would take about 60 shuttles.(4)

Being stuck in a small, enclosed space with the same group of people for years on end is possibly the most dangerous to the astronauts' psychological well-being. Crew have to wait a long period of time to reach mars and the fact that there is only a thin wall separating them from a vacuum of space.(8)

Minimizing consequences:

Space astronauts need to follow a strict workout routine to prevent the loss of bone and muscle. 6 months is the minimum time they will be needed on mars. Muscle mass decreases at a fast past and it requires a high-weight, low-repetition workout to maintain the correct mass. The aRED (Advanced Resistance Exercise Device) is the first piece of NASA exercise equipment to meet this need. (6)

To minimize the effects of radiation astronauts have special suits and rockets to help prevent this affecting their bodies. These suits shield against ultra violet and particle radiation.

(4)www.astronomycafe.net/qair/q2811.html
(5)http://www.wired.com/wiredscience/2010/08/astronaut-muscle-waste/#ixzz0zovBXlxX
(6)http://www.wired.com/wiredscience/2009/04/astromuscles2/
(7)http://science.nasa.gov/science-news/science-at-nasa/2004/17feb_radiation/
(8)http://www.jyi.org/volumes/volume6/issue5/features/cull.html

Conclusion

We have calculated that a manned, return trip to mars would take at least 152800kg of fuel. This is a combination of solid fuel and liquid fuel, in the same proportions as a space shuttle consumes.

The bulk of this fuel is used in escaping the Earths atmosphere. The remainder is used in escaping Mars's atmosphere. This is a much smaller proportion since the gravity on mars is less than earth's due to its smaller mass. The weight of the rocket by this time of the journey will also be significantly less.

Other, more modern, fuel types may be required if a mission of this type is really to occur due to the length of time it would take to travel to mars and the consequences on the astronauts.

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