

Advanced Concepts in Space Propulsion

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The question of how to send men to Mars is not a single question, but many smaller questions summed up into one. For instance, how much food and supplies would a manned crew be able to bring with them? How can we circumvent the debilitating effects of zero gravity, which results in the loss of calcium and decreased bone density? How much solar radiation and Cosmic Background radiation will our astronauts be exposed to, and how can we reduce that amount? What happens in the case of a medical emergency? Can man survive the psychological toll of a trip that takes him tens to hundreds of millions of miles away from his home? There are many different ways in which one or another of these particular problems can be approached, but only one way to alleviate or eliminate the problems caused by *all* of these questions at once: invent a more efficient way of traveling to Mars. The purpose of this paper is to present the reader with the current options and future possibilities of space propulsion, and to then point out which method or methods are best for substantially shortening the time it takes to get to Mars and increasing the mass of available payload. I will first present the ideal forms of space propulsion, which currently are far beyond our scientific abilities but may one day take man further from earth at faster speeds than ever before. Next I will return to current forms of space transportation, and discuss the methods being considered to improve our existing systems. The paper will end with a lengthy look at the near future; the forms of propulsion that will be the next step in space exploration, and which of these new methods will be the most suitable for a manned mission to the red planet. I will claim that the best option for space propulsion to Mars in the present is nuclear propulsion, and the best technology to develop for future missions is antimatter propulsion.

There are two goals which must be met to achieve the “ideal space propulsion system.” The first goal is to create a form of transport that does not rely on on-board propellant. This would entail using or changing the properties of space-time, harnessing the energy available in space, or having a completely reusable source of energy on-board (which technically means relying on the propellant that is brought along, but if it is “re-chargeable,” then the inconvenience is practically negligible). The purpose of this is to maximize payload capabilities, as well as to allow an infinite lifespan to the duration which the space vessel may be in flight and making course changes. The second goal is to achieve speeds close to (or possibly surpassing) that of light. This would shrink the whole of our solar system down into an easily accessible domain, as well as bring the stars at last into the reach of mankind.

NASA established in 1996 the “Breakthrough Propulsion Physics Program” to come up with all possibilities, regardless of how far removed they are from our current capabilities, of how to achieve these two goals. There are several possibilities, all of which assume there will be breakthroughs in theoretical physics that will show what we think of today as impossible may be possible. For instance, it is assumed that an asymmetric field can be generated around a vehicle that will in turn accelerate itself. A gradient will therefore be located at the center of the vehicle, which results in a reaction force that propels the vehicle. If the field is not asymmetric, the net force will be zero, and therefore useless in propelling the vehicle, which is why an asymmetric field is inferred. This is known as a Diametric Drive, and is identical in practice to negative-mass propulsion. [1, 3] Although particles of negative mass (sometimes known as tachyons) are not positively known to exist, recent astrophysical observations have indicated a type of exotic matter that may have gravitational repulsion, causing the universe to accelerate its expansion. These particles necessarily would have negative mass to cause such an effect; and therefore the idea of a Diametric drive would not be that far fetched.

Similar in concept to the Diametric Drive is a Pitch Drive, which operates under the same basic principles as a Diametric Drive, with the exception that the asymmetrical field can be created without the pair of point sources. [1, 3] It is unknown whether this is possible. This would further reduce the mass of the space vehicle, which is why it is considered a more ideal system than the Diametric Drive. The Bias Drive [1, 3] operates on the assumption that the properties of space itself can be altered, such as changing the local value of the Gravitational Constant “G” in front of and behind the vehicle, producing an asymmetric field around the ship. A problem with this concept is that there would be a singularity in the gradient of the field inside the vehicle.

A concept very similar to the Bias Drive, and familiar to many fans of the popular television show “Star Trek,” is the Warp Drive concept by Alcubierre. [1, 3] It presents the possibility of stretching and shrinking space-time *itself*, and creating an asymmetric field that would accelerate the vehicle in this manner. The subtle brilliance behind this concept is that the laws of special relativity hold only in space-time; we do not know if there is a fastest possible speed if space-time is altered. Therefore we enter the possibility of faster than light travel into the mix of potential propulsion systems.

Another idea that was explored by the NASA committee was a Disjunction Drive. [1, 3] The premise behind this form of propulsion is that the field that is used can be disassociated from the field source. This concept has the benefit of not relying on an asymmetric field; however, it assumes that it is *possible* to disassociate a field from its source. Although this has not been disproven, there is strong opposition to the notion. Picture a bar magnet zipping along across the room, since the source of its field lines are 2 centimeters to the left or right of the location of the magnet!

There are several common themes that tie together the “Drive” methods proposed by the Breakthrough Propulsion Physics Program. None of these would require an onboard source of

propellant, and therefore could operate for an indefinite amount of time. All of these propulsion systems offer the possibility of travel at relativistic speeds, or possibly even super-luminous speeds, by the use of asymmetric fields and/or the distortion of space-time.

A final idea that has received much attention that does not involve induced fields is tapping into the Zero Point Energy Field, also called the ZPF. Quantum Mechanics dictates that there is no such thing as an exact amount of energy in an exact location, as a byproduct of the Heisenberg uncertainty principle. Therefore there are endless undulations in the energy of a vacuum, which most noticeably demonstrates itself in the Casimir Force. By tapping into this energy (which has been estimated as being as high as 10^{14} Joules per cubic meter [1]) which exists everywhere in space, there would be no need to carry any propellant around in a space vehicle. It would all come from utilizing the natural energy of space. Specific models of utilizing this energy are difficult to imagine at present day, but analogous models include a Hypothetical Differential Sail, which would use Cosmic Background radiation as its source of varying energy to create a gradient in pressure that would accelerate a vehicle. [3]

The development of ZPF propulsion the above mentioned “Drive” propulsion techniques would no doubt change life as we know it drastically. A trip to Mars, even at its furthest distance from earth of over 200 million miles, would take less than half an hour if relativistic speeds could be attained. An unlimited supply of cargo could be brought from earth (or from Mars to the earth, for that matter) using a propulsion system such as the above. Therefore these types of propulsion are ideal for Martian exploration, and are the best options of all those that will be mentioned in this paper. However, it would take a breakthrough of gigantic proportions in not only engineering, but *physics* first before these ideas could be put into use. There is also the question of how to launch a ship of such magnitude. Could a Bias Drive be used on the surface of the earth without distorting the planet’s surface and the life on it? And what of the engineering difficulties in constructing a vessel that can withstand the conditions these proposed

propulsion systems would generate? These are unaddressed questions at the present moment. Regardless, it is safe to say that for now these ideas remain as purely theories. If we are going to go to Mars, we cannot wait until these systems are feasible. We will leave these propulsion systems of the distant future to take a look at the forms of space propulsion we face today.

Today's method of Space Exploration is dependent on chemical rockets. A violent burning of chemicals provides the thrust to escape into orbit; another burst sends the vehicle on its way to its final destination. After that, there is no more acceleration for the vehicle. "For 40 years NASA has been doing planetary science in the same way. That is, you accelerate for 5, 10, 15 minutes, and then you stop. And you coast, and you coast, and you coast," says Ed Weiler, NASA's chief scientist. "That's not the way to do exploration." [6]

Nevertheless, there are ways to improve on the current methods without changing the overall design. For instance, if the fuel that powers our rockets can be more concentrated, then there is more available mass for payloads. One of the fuels being investigated now at the Glenn Research Center is using "solid hydrogen and atoms," according to John Cole, a manager in the Advanced Space Transportation Project Office at NASA/Marshall. [4] "You can get as much as 10 times as much energy out as you would from conventional combustion," explains Cole. It is also possible to take three carbon atoms out of benzene, which itself burns quite well due to being built around rings of six carbon atoms, to produce bicyclopropylidene. [4] Not only does this have a greater potential energy, but it is also over twice as dense as the refined fuels burned in the first stage of many rockets. This allows substantially less fuel to be used to lift the same mass, thereby increasing the payload amount considerably. It would not, however, increase the speed at which a trip to Mars could be made by any significant amount.

One other recent innovation that could improve slightly the performance of present day rockets is a ceramic matrix composite turbine disk, developed at NASA's Marshall Center. [5] The turbine in the typical rocket provides power to the pumps that pressurize the engine

propellants, and is a metallic disk with separately attached blades. The continuous composite ceramic disk developed at Marshall can withstand temperatures of up to 2,000 degrees Fahrenheit, whereas the typical metallic disks can only tolerate temperatures up to 1,200 Fahrenheit. The increased heat tolerance of the ceramic disk translates into a lower usage of fuel; the increased engine efficiency then allows for a higher payload weight. Quantitative measurements of the increased payload are not available.

Electric Propulsion is a line of space drive that has recently come into use. Electric Propulsion technologies

generate thrust via electrical energy that may be derived from either a solar source, such as solar photovoltaic arrays, which convert solar radiation to electrical power, or from a nuclear source, such as a space based fission drive, which splits atomic nuclei to release large amounts of energy. [11]

There are two main types of electric propulsion technologies that are in use, or could be used, in the present day. These are ion propulsion drives and nuclear fission drives.

An ion propulsion engine was first launched into space on October 24th, 1998 on Deep Space 1. The system expels positively charged xenon atoms out the back of the engine at a speed of 100,000 km/h, yet produces just a fiftieth of a pound of thrust (although it is ten times more efficient than a chemical rocket). [7, 8] Powered by 2500 watts of electrical power that its photovoltaic cells pick up from the Sun, this miniscule thrust will add up to a speed of over 16,000 km/h in about 20 months. [9] The wonderful thing about propulsion in space is that there is no retarding force of friction to slow an object down. Therefore, every burst of speed stays with a vehicle, accumulating over successive firings (or continuous firings) of the engine. JPL has recently designed a xenon fueled engine that will last seven times longer than the one on Deep Space 1, and therefore would be able to obtain faster speeds than any made made object ever has. [10]

Ion engines have long been studied and recognized as potentially useful drive systems. In the 1950's, Werner von Braun wrote that ion engines are, "effective for missions to the more distant parts of the solar system." Although this is true, there seems to be no practical use of Ion engines for travel to Mars. Consider the following: it took Deep Space 1 over 20 months to build up a speed of 16,000 km/h. This is a lower speed than our current chemical rockets fly at, and they are capable of making the trip to Mars in under nine months. The trip to Mars would take years on an ion engine. Thus, an ion engine would be more suitable to exploration of the Oort cloud or Pluto than a chemical rocket based probe, but not for something as close to earth as Mars.

Another type of engine that has proven its success, though it has not received much usage, is the nuclear fission engine. Nuclear engines can operate in a variety of ways. For instance, if liquid hydrogen is pumped over the reactor core, the superheated gas can be expelled out a rocket nozzle in the back as a sophisticated form of fuel. [4] The process itself is non-radioactive throughout the pre-launch and launch activities, and would not begin until after the fission based vehicle is brought into earth orbit by a chemical rocket. The craft would supply all of its own electricity through the radioisotope thermoelectric generators. [6] Most importantly, the time scale would be significantly reduced with a fission space drive. Crewed voyages to Jupiter could conceivably last under a year, and a round trip to Mars could be cut down to 12 weeks. [4, 6]

Nuclear fission technology has already been demonstrated on a somewhat smaller scale, with the nuclear-powered *Cassini* spacecraft in 1997. *Cassini* and its 72 pounds of uranium have long been in space now, and are working very well. A larger fission engine should propel a human crew to Mars quickly; however, it still requires a chemical engine to achieve earth orbit, with the nuclear engine as part of the payload. A fission reaction based engine likely would not be approved as an earth-to-earth orbit rocket due to the politics of the world we live in today.

The idea of having a nuclear engine (disregarding the complete uselessness of a nuclear engine as a weapon) launched into the atmosphere is currently a proposal that most governments would hesitate at. Environmentalists would protest, bringing up the potential consequences of radiation to our planet if the rocket were to fail to achieve orbit. Also, polluting space with radiation is an argument often brought up against nuclear propulsion. This last statement is without merit, for radiation is the natural state of our universe. The same reasons which make the engine useless as a weapon will make it relatively safe on the environment; essentially, the fact that it will be designed to be kept “off” until earth orbit is left, and that the reaction itself is a controlled reaction. An uncontrolled reaction, such as that in an atomic bomb, is terribly inefficient for propulsion purposes.

And so we exhaust the current methods of space exploration. Nuclear fission propulsion is the quickest and most efficient method that we possess today, and therefore should be incorporated into the most immediate plans for Martian exploration. The great irony in using nuclear fission for manned space missions is that since it produces constant acceleration, thereby quickening the journey to Mars, it will lessen the amounts of radiation the crew will be exposed to. Of course, there are surely possibilities for engine designs within the scope of near-future research that will be quicker and able to carry more payload than nuclear fission. Scientific advances are close to bringing to fruition many new and powerful solutions to space travel, which will each be useful in a variety of ways. The goal now is to target the most useful future space propulsion concept for travel to Mars. None of these will be completed in time to be used for the first Martian mission, but they will bring forth the next great revolution in space travel that *will* one day be incorporated into manned spaceflight.

At the new Marshall Space Flight Center, soon to be under construction, one of the laboratories will be dedicated to the field of beamed energy propulsion. The reason for this area of research, according to the scientists at Marshall, is that “spacecraft powered by microwaves or

lasers could deliver better performance than conventional chemical-fueled systems because most of the heavy energy source would remain on the ground or in orbit, separate from the vehicle.”

[13] Developed by Professor Leik Myrabo of RPI, the Lightcraft is exactly the type of vehicle for which Marshall is looking. The underside of the vehicle is a parabolic mirror that focuses incident laser beams to the outer ring of the craft, which heats up the air between 18,000 and 54,000 Fahrenheit, well beyond the point of combustion in those areas. The explosions in turn propel the craft. [14, 15]

However, for a craft much bigger than the size of a model, a laser larger than one ever constructed would be needed. For this reason, the design has been altered to use microwaves instead of lasers, microwaves being a more advanced field of study. [14] The design of a microwave based vehicle would consist of a pressurized helium balloon type structure that makes the craft partly buoyant, and simultaneously serves as a large reflector for the microwave beams. On the top would be solar cells, and the craft would be encircled by superconducting magnet rings with a series of ion engines. [14] At take-off, speeds would be only in the 50-100 km/h range, but would only be working off the ion engines. The microwave beam propulsion focuses hot air on one side or another of the vehicle, causing a temperature gradient that accelerates the vehicle. When the superconducting magnets kick in and cause the microwaves to form a nose cone for the flying disk, speeds greater than 25 times the speed of sound can be achieved. With this system, it is estimated by professor Myrabo that a trip from the earth to the moon would be reduced to approximately 5 _ hours. [14]

However, It must be pointed out that there are many technologies that first need to be advanced before a final working vehicle of the sort can be tested. The microwave source would need to be a one kilometer satellite. Also, the payloads of such craft do not appear to be sufficient for a manned crew. Although it would be an advantage to separate the propulsion source from the vehicle itself for payload benefits, for the energy source of the vehicle to be in

earth orbit while the vehicle travels over a hundred million kilometers away to Mars is not very safe. The source of propulsion should be localized in the vicinity of the ship at all times, so the vehicle's crew has direct control over its own course.

There are two more ideas regarding only the aspect of putting a payload into space that I would like to address at the moment. One is the idea of using a magnetic track to accelerate and send into flight a space vehicle. The magnetic levitation system being explored by the Marshall laboratories of NASA would drive a spacecraft along the track until it gains sufficient speed, when an onboard engine would kick on and send the vehicle into orbit. [17] A one and a half mile track could accelerate a ship to over 90% the speed of sound in nine and a half seconds. The offboard source of energy – the electricity used to power the track – is a factor that would help to reduce the weight of the vehicle, resulting in cost savings (electricity is a cheap fuel) and increased payload. However, chemical engines are still required on such a vehicle to propel it into orbit, and does not increase the overall speed in transit between the earth and Mars. In essence, a magnetic levitation device could increase payload slightly for a Mars mission, but could do nothing on its own to reduce the time of the mission.

A very old idea about how to get into space is the so called "Jules Verne Gun," aptly named for the French writer who dreamed up its existence almost 140 years ago. By creating a sufficient initial velocity, an object would be able to achieve orbit from a single initial thrust. The initial velocity required, 4.35 miles per second, is currently being pursued at Lawrence Livermore National Laboratories with large gas guns. [16] However, an attainment of these speeds is not really a huge success. Disregarding the fact that there is no beneficial extra speed gained when in orbit from this system, and that an incredibly large gun would be required to launch objects over a few tons, the initial acceleration is over one *thousand g's*; far more than can be survived by humans. [16] The only use that such a system would have would be as a reusable, continuous way of launching supplies or parts into orbit for the purpose of loading onto

a vehicle waiting in orbit, or to assemble a vehicle in earth orbit. Most of the dangers of Martian travel are not addressed at all by this technique.

The main obstacle in achieving fast transit between Earth and Mars is *not* the launch, however; it is traveling in space itself. An idea which has been considered for quite some time is the usage of solar sails. Thanks to quantum physicists of the early 20th century, we know that light has a momentum. By placing a large lightweight sail in space, the intensity of the solar luminosity will push on the sail, causing a slowly increasing total velocity. While the obvious plus side is that no fuel is needed for such transportation, there still remains the object of how such a large object will be placed in space. Conventional chemical rockets yet again will likely do this work, limiting the total payload. A solar sail's velocity would approach a constant as it moves further from the sun, but since we are looking at only from the earth to Mars, the intensity remains fairly strong, remaining above 40% of the intensity at the earth's distance from the sun. The sail's velocity can reach after some time a speed of 240,000 km/h; unfortunately, my sources do not say how long the sails must be working for before this speed is achieved. [18]

Nevertheless, the time required for high enough speeds to be obtained that surpass that of a chemical rocket *is* longer than 9 months, so the idea of using solar sails for manned missions is not beneficial. However, couldn't solar sails be used to carry the supplies needed to Mars, free of fuel costs? True, it could – but how do you slow the sail? Contracting the sail would eliminate acceleration, but wouldn't do anything to decelerate the vessel. Ultimately, another type of rocket would be required for braking this vehicle, which makes solar sails inappropriate for a mission to Mars.

A concept similar to that of solar sailing is magnetospheric plasma propulsion. In this type of propulsion system, a magnetic field is generated and then injected with ionized gas (plasma) that drags out the field lines to form a plasma bubble around the vehicle. [19] Dr. Robert Winglee of the University of Washington has worked on such a drive, which is capable of

generating a magnetic field of .1 Telsa through a conventional solenoid and operating for three months on only 3 kg of helium. Solar cells would provide the 3 kilowatts of electricity to run the magnet and plasma generator. The force of the solar wind against the magnetic field of this vehicle, which weighs 136 kg, would accelerate it to speeds of up to 288,000 km/hr; 10.5 times faster than the space shuttle. [19]

Once again, the magnetospheric plasma propulsion system suffers from the inability to stop itself on demand. While more promising due to the ability of forming its own magnetic field to be pushed off of, there is the question of how this vehicle would be able to carry with it any vehicle which has human life on it without exposing it to severe magnetic fields. (.1 Telsa is a thousand times stronger than the earth's magnetic field) Also, the author of this article fails to mention the rate at which the craft will accelerate. While I believe it would be faster than a solar sail, I cannot be sure of the time frame it requires to build up speeds faster than that of conventional propulsion today.

While magnetospheric plasma propulsion would harness the momentum of light, a property which was discovered only in the past century, the most famous physics discovery of the past century could far surpass this propulsion system in terms of usefulness. "Antimatter propulsion" is an idea that sounds to most people like complete science fiction. After all, hearing statements such as "a gram of antimatter would carry as much potential energy as 1,000 Space Shuttle external tanks carry," is too much to believe. [20] However, not only is it true, but antimatter is researched, created, and even *collected* in particle accelerators across the world. There is much research currently being conducted on how to harness the energy in antimatter for propulsion devices. According to Harold Gerrish of the Marshall Space Flight Center's Propulsion Laboratories, the simplest antimatter engine would consist of antimatter/matter reactions heating a tungsten core which heats hydrogen as it flows in and out of the nozzle, creating a specific impulse of twice that of the space shuttle. [20] It is also possible to use an

antimatter/matter reaction as an ignition to a fusion or fission reaction in a propulsion system.

[22] With these conservative antimatter propulsion designs, 6 weeks is a reasonable amount of time for a one-way trip to Mars. [23] Penn State is working on developing the Ion Compressed Antimatter Nuclear engine, which would use antiprotons to implode pellets that have nuclear fusion targets at their core, creating a series of small blasts that would rapidly propel the vehicle through space. [20] This type of propulsion is fast enough to place almost all of the planets within reach of manned missions.

There are several problems with antimatter propulsion devices. First of all, there is barely enough antimatter to go around. Only the CERN accelerator, Brookhaven laboratories and Enrico Fermi Labs produce a substantial amount of antimatter each year. Annual production of antimatter is only two *billionths* of a gram. [22] Part of the reason for this is the difficulties faced in capturing and storing antimatter. Since it has the desire to annihilate itself whenever it comes into contact with matter, the two must be kept separate. For this reason, for every million antiprotons created, only one is successfully captured and stored. [20] Therefore, with sufficient advances in storage of antimatter, annual production could rise from the billionths of a gram to whole milligrams! Explains Doctor Gerald Smith of Pennsylvania State University, “Our aim is to get up to a microgram of antiprotons. There are some interesting propulsion techniques that work at that level.” [23] However, it should be noted that Dr. Smith is currently working on the most advanced anti-proton trap to date, which is only capable of holding under a nanogram of antiprotons for a time span of about 5 days; and the “trap” weighs 100 kg as well. [23] It would be fair to say that *significant* advances in storage are necessary before these devices become the wave of the future. It is interesting to note that if one day we are able to harness the full power of a particle/antiparticle interaction, travel time from the earth to Mars could be reduced to a single day. [22]

Antimatter drives, like fission drives, do not require a long time to “warm up” and get moving at great velocities. Therefore, they are ideal for transporting people from earth to Mars. With only fractions of a gram of propellant needed for a reaction, the only weight needed to be accelerated is the payload and the ship itself. This greatly increases the mass of payload which can be brought on the trip. Whether or not antimatter drives can be used for take-off from earth hasn't been explored fully, but the thrust generated *can* be made to be greater than that of chemical rockets – depending on the engineering style of the vehicle. Antimatter propulsion would be an *almost* complete space vehicle, since there is a need for propellant on board, and requires refueling. However, it would surpass the fission drive in terms of thrust generated and specific impulse, and would reduce the travel time to and from Mars. This is why I advocate an antimatter propulsion system be incorporated into manned Martian expeditions as soon as it is a feasible option.

The final type of space propulsion which I will discuss is the fusion reactor. Scientists have not yet reached the “break-even” point with nuclear fusion; that is, they have not yet been able to get more energy out of the reaction than they had to put in to get the reaction to happen in the first place. “We are about 5 years away from the break-even point in fusion,” says Dr. Robert H. Frisbee of the Jet Propulsion Laboratories. [24] The difficulty for NASA in adapting fusion to a space drive is to have the reaction occur at a high enough rate that it produces a significant amount of energy, but not too much that would cause excessive heats to be produced. The current methods used to produce nuclear fusion are magnetic confinement and inertial confinement. Unfortunately, magnetic confinement fusion has too low of a yield to be useful in propulsion systems, and inertial confinement laser fusion produces a density 1,000 trillion times greater than magnetic confinement – far too high to keep cool. [23] In addition, current fusion equipment weighs several hundred metric tons. The weight of the engine itself would be tens of

times greater than a single shuttle cargo payload. [23] Until more advances are made in fusion processes, harnessing its power in space is beyond our reach.

I should point out that if nuclear fusion can be achieved as a feasible propulsion system, it would be very advantageous over current systems, including nuclear fission. Just like an antimatter system, a large amount of energy could be produced from a relatively low mass of material. In addition, since fusion is cleaner than fission, it may be possible to use fusion as a source of launch direct from earth, bypassing chemical rockets all together. The main reason why I advocate antimatter propulsion over nuclear fusion is because antimatter propulsion, in its most advanced form, converts nearly 100% of the rest mass of a particle into energy. Nuclear fusion, at its best, converts only 0.7% of the rest mass of its fuel into energy.

It is my conclusion that the greatest amount of attention should be placed on building antimatter based propulsion systems for the end of this century, and to incorporate nuclear fission engines into modern space travel missions. The great reduction in time of transit and incredible increase in payload capabilities will more than make up for the work which must be done to fully develop antimatter propulsion. Until that day comes, fission propulsion will reduce the length of manned trips to Mars to at least half of what it would currently take using a typical chemical-powered rocket. While it is true that radioactivity on earth in large doses is something to avoid, space is a continuous source of radiation that poses a hazard to the health of humans with each passing minute spent in the vacuum of space. Using a fission rocket in this medium is not destroying a pristine environment, as we have seen fission powered bombs do on earth. It is but a means to an ends; a way of lessening the hazards mankind must face on its dangerous quest to explore Mars.