Challenges of Building a Starship in the 21st century

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Abstract

There have been many excellent books and articles that address the difficulties of building a starship. Most approach it from a theorhetical perspective and discuss the physics and technical challenges. Rarely do they approach it from a comprehensive engineering point of view. The general conclusion in most of these books and articles is that with current technology it is not possible to build a functioning starship to the nearest stars. I wanted to take a different approach and assume we had to go to the stars and do it during this century. This assumption means we can only use technology that either exists or with minor extrapolation, could be available. What would such a starship look like? Would it be possible? Rather than wait for a better, or perfect starship technology, my perspective was a variation of the expression attributed to Voltaire of "don't let perfect be the enemy of good".

The conclusion is that while technically feasible there are several very large requirements that have to be fulfilled- the largest being that much of the starship mass required for acceleration and deceleration would have to be picked up enroute via millions of packets launched in the path of the starship.

A more complete analysis is included on the web site: https://www.allthingsspace.info

Introduction

Even though the technical challenge of building a starship are formidable, to a much lesser extent, the same could be said about building a reusable rocket. For fifty years reusability has been an acknowledged requirements for making space accessible for travel, colonization, and resource exploitation. And for fifty years, little progress was made. The Space Shuttle was re-useable but the labor and difficulties of refurbishing it between launches meant that each flight cost, by some estimates, $500 million. For many decades the prevailing wisdom was that a privately developed reusable rocket would never occur and that the technology was not yet available to make a reusable rocket that was both cheap and reliable. This was the prevailing wisdom until SpaceX came along early in this century. Within little over 10 years, using a partly reusable first stage, SpaceX succeeded in reducing launch costs by 75% all why developing the most reliable rocket ever built… the Falcon 9. To make this happen, there were no unique technologies that were invented or required. Rather SpaceX built on the knowledge of the prior half century and applied it in new and creative ways.

I believe that part of the reason SpaceX has made so much progress is that instead of using all the reasons why something can't be done (or only done with vast amounts of dollars) and waiting for the perfect technology, it takes the position that something can be done, done with current technology, and relatively cheaply and quickly. Using this philosophy as my guide I decided to answer the question from the perspective of "rather than wait for a better technology suppose we **had** to build a Starship this century?" What would it look like?

The reasons for the design choices I made are greater than this article can cover so in some cases I will only state the conclusions. However, I will review several of the most important results:

1) To escape the solar system and maximize our velocity, we will need a two-stage configuration
2) 300kps is about the highest velocity we could reasonably attain. This means that our voyage will be over 4000 years to the nearest stars, or 10,000 years to go to 10LY.
3) We will need nuclear power plant that is both lightweight and high power- able to generate at least $20W_e$/kg of reactor mass.
4) It is not possible with current technology to build a starship and dispatch it from our solar system at high speed and have it slow down at the target star. This will drive us to a mission profile whereby most of our reaction mass needed for acceleration, as well as mass required for cosmic ray protection, resupply and deceleration is supplied via enroute packets picked up in the path of our starship. In this article I will review why this is a requirement as well as some of the engineering and manufacturing challenges of delivering these packets to our starship.
5) A version of a mass driver will be the preferred primary propulsion system both for the starship and for the packets that are delivered to our starship.

Problem Scope

The space between stars is vast and current spacecraft travel extremely slow. If the sun were reduced to the size of a typical marble the earth would orbit about 1.4 meters and Neptune about 40m away. On this scale the nearest star would be about 370 km away. The furthest a manned ship has traveled (the moon) is the equivalent of 3mm, though uncrewed automated spacecraft have gone over 150m away over about 50 years of travel.

A starship is a complicated system of payload, power, and propulsion with frequently conflicting requirements. Changing any one aspect will have a cascading effect and force change to other parts of the ship. However, when designing the starship the overriding challenge is velocity. Velocity is inextricably intertwined with the need for energy. With enough energy (and the ability to control it) these distances are surmountable. Unfortunately, nearly unlimited energy does not exist and to get more energy we have to build larger and larger power supplies that make the mission more and more difficult. Ultimately, we need a tremendous quantity of energy with a small power plant mass.

To more appreciate these challenges, we need to look at a key equation which determines the performance of a rocket- the so-called rocket equation. This equation determines or rockets' performance.

EQUATION 0-1 $\boldsymbol{\Delta V = v_e \ln\left(\frac{m_0}{m_1}\right)}$

Where:

$\Delta V = Rocket\ final\ velocity$

$v_e = exhaust\ velocity$ (usually expressed by the term Specific Impulse (Isp) in seconds multiplied by the acceleration of gravity- 9.81mps)

$m_o = starting\ mass\ of\ rocket\ (payload, structure, fuel)$

$m_1 = final\ mass\ of\ rocket\ (payload\ and\ structure)$

The ratio $\frac{m_0}{m_1} = is\ called\ Mass\ Ratio\ (MR).$

Using the rocket equation, we can determine the performance of a spacecraft knowing only two parameters- the Specific Impulse and the Mass Ratio (MR).

Requirement - the need for High velocity

The Saturn V is to date the largest and most powerful rocket successfully flown. At lift off it weighed about 3000 mt and it had the ability to launch about 140mt into orbit with a velocity of about 7.9kps. If we could place a fully loaded Saturn V in orbit and launched from there, we would have a slightly greater performance since we would not have the drag through the lower atmosphere, gravity losses (the loss of performance from launching vertically) and would have slightly higher v_e because rocket engines have higher performance (specific impulse) when operating in the vacuum of space.

Would the Saturn V make an effective starship? Using the average performance and mass numbers for a Saturn V, with a final mass of 140mt and running them for the three Stages of our Saturn, we would get a rocket whose final velocity would be about 9.62 kps. While 9.62 is an impressive velocity, it is only .003% the speed of light. It would take over 130,000 years to reach the nearest star. (In reality, it might have difficulty even leaving the solar system since at the earths distance from the sun the escape velocity is about 42kps)

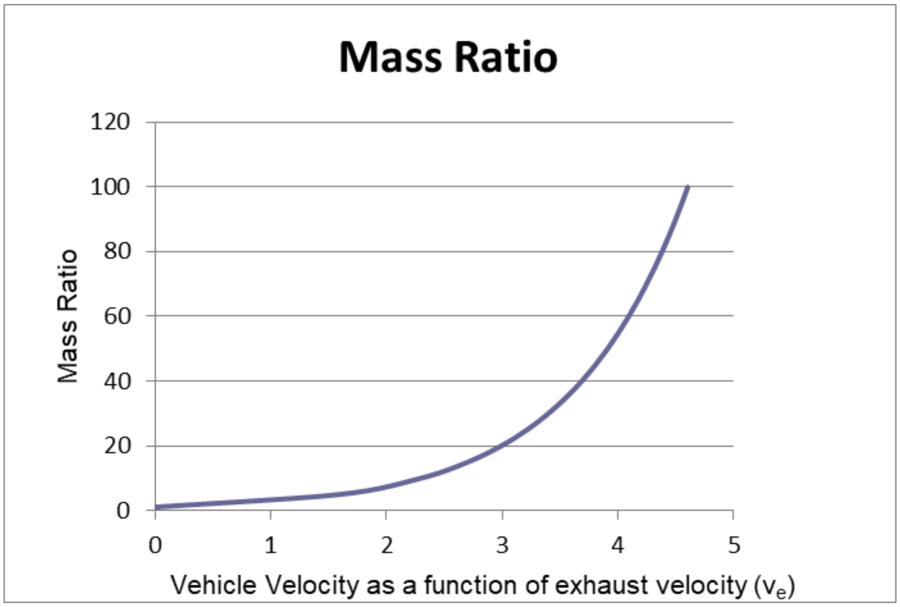


Figure 0-1 Mass Ration vs Velocity as function of Exhaust Velocity

Since MR is a natural log function, greater and greater MR provides less and less increase to your final velocity as shown in figure 0-1. The only other way to get a higher velocity is to increase your specific impulse and have a high exhaust velocity. However, the kinetic energy (KE) equation determines how much energy is in our exhaust velocity. This equation, familiar to high school students everywhere, is:

Equation 0-2 $KE = \frac{1}{2}mv^2$

This shows us the other half of the problem- our exhaust velocity is the square of the energy given to it. To double our v_e, you need to square the energy.

Chemical reactions as used for all current rockets launched from earth are limited by the amount of energy that can be liberated when the fuel is combined with oxidizer. It is true that the temperatures liberated in rocket fuels can melt most metals, but there are usually engineering fixes to these problems. As a rough rule of thumb, specific impulses are directly related to the square root of the exhaust temperature divided by the molecular weight of the exhaust products. The primary limitation for a chemical rocket's performance is the limited amount of energy (temperature) liberated which ultimately limits their exhaust velocities.

Let's come up with a hypothetical starship that uses the highest performance chemical rocket typically used - a vacuum optimized engine derived from the Space Shuttle Main Engines (SSME) that burns hydrogen and oxygen. We will assume a specific impulse slightly higher than the original SSME design (460 vs 453) to reflect a larger engine nozzle and higher chamber pressure. Using a single stage with a MR of 20 we would arrive at a final velocity of about 13.5kps.

As seen in Figure 0-1, a 20 MR is probably the sweet spot where our final ship velocity is about 3x our exhaust velocity. An MR of 100 will give our final velocity a little less than 5x our exhaust velocity… demonstrating a point of diminishing returns. From an engineering point of view, a 20 MR is difficult if we wanted to launch from earth, since the structure (mainly fuel tanks) would be very large, it would be subject to large aerodynamic forces, and you would have to have massive engines for lift off. However, in space where the gravity and aerodynamic forces are non-existent, an MR of 20 is doable but an MR of 100 is challenging and depending on the fuel which determines the requirements for the fuel tanks, is probably not doable.

The problem with this analysis is that it does not address the need to stop at our destination. For an interstellar voyage we want to decelerate at our target star/planet which will require the same MR that we needed for our initial acceleration. For our ship that accelerates to three times its exhaust velocity and slows down at the target star we now need a total MR of 400. If we built a ship that massed 10 mt, which including our structure mass (engines, power supply, payload, and empty fuel tanks) our initial staring mass fully fueled, would have to by 400,000 mt. Building a fuel tank to store 390,000 mt of fuel but that weighs less than our 10mt mass available is very difficult and beyond our current capabilities. The only way of reducing our MR is to increase our v_e or decrease our starship velocity.

There are propulsion engines that have specific impulses in the thousands and are called electric propulsion- either ion or plasma. They take individual ions and accelerate them with magnetic fields to very high velocity. However, their thrust is very low- frequently a fraction of a newton. This goes back to the fact that tremendous power is required to increase exhaust velocity substantially. Furthermore, electric propulsion are not as efficient as a chemical rocket at converting thermal energy into thrust. Traditional chemical rocket engines are usually over 90% efficient converting energy into thrust whereas electric propulsion thrusters are typically around 50% efficient in converting electric power to thrust. Furthermore, nuclear reactors or RTG's convert only a portion of their thermal energy into electrical- in the case of a typical earthbound reactor, about 1/3rd, or in the case of an RTG only about 7%.

For a chemical rocket or electrical propulsion, we can figure out a typical fuel consumption by using the equation:

EQUATION 0-3 $F_{Thrust} = \dot{m} v_e$

Where $\dot{m} = mass\ flow$

And rearranging the equation to calculate $\dot{m} = mass\ flow$

EQUATION 0-4 $\dot{m} = \frac{F_{Thrust}}{v_e}$

The NEXT engine, a successful electric thrust engine used on some current NASA spacecraft puts out about 236mN with a specific impulse of 4200 sec and uses about 7kw. At this thrust and v_e the calculated mass flow is about 5.73×10^{-6} kg/sec. This works out to 1kg of reaction mass used every 2 days. If we used electric propulsion on a starship the size of a Saturn V with a 3000mt m_0 and an MR of 20, we would have 2850mt of reaction mass and we would take 15,770 years to expel all this mass! So while a high specific impulse is a requirement for a starship, our thrust (and hence mass flow rate) must be hundreds of times higher than typical electric propulsion which would require hundreds of times more power. In theory our 4200 second NEXT engine with a MR of 20 could bump our speeds up to about 123kps. Many electric propulsion engines, with appropriate design modifications and given enough power can have specific impulses of up to 10,000 seconds. If we had an electric propulsion with a specific Impulse of 10,000 we could achieve a velocity of 300kps and a 4300 year voyage time to the nearest star.

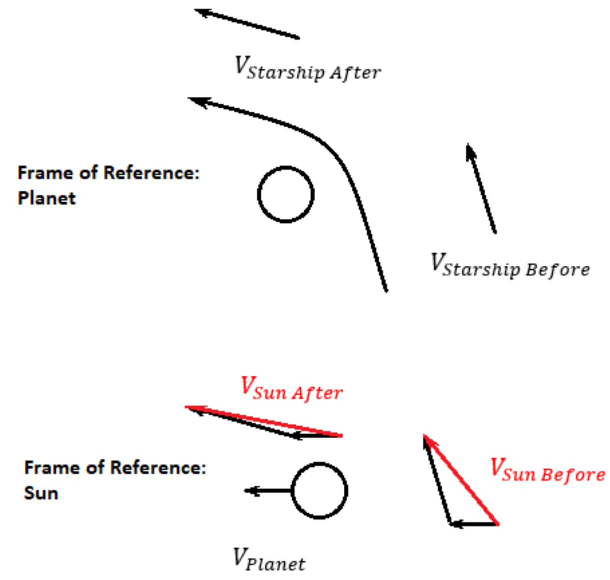


FIGURE 0-2 GRAVITATIONAL SLINGSHOT PLANET AND SUN REFERENCE

The low force provided by electric propulsion also creates another challenge- escaping the sun's gravity. Electric propulsion does not have enough power to propel a starship directly to another star- rather they will cause our starship to slowly spiral away from our sun. Depending on the thrust to mass ratio, it can take decades or even centuries to reach solar system escape velocity. During this time the spacecraft will have swung around the sun in a widening spiral without traveling toward its target and wasting a large portion of its fuel.

There are some tricks which may be able to boost our velocity- including a Gravitational Slingshot (Figure 0-2) using a planet (usually Jupiter) to boost up the velocity by a few kps. This may be enough to throw us out of the solar system after only a few years of acceleration with electric propulsion. However, this technique can typically add no more than about 10kps and would only work toward boosting velocity in the direction of the planets (in this case Jupiter's) travel and unfortunately nearby stars are not located here.

Solution - Two Stages- Achieving Solar System Escape Velocity

The partial solution to this issue is to develop a two-stage rocket with the first stage having a high thrust chemical or nuclear rocket and combining it with an Oberth Powered Maneuver which will allow our starship to reach a moderate escape velocity quickly. Once this stage is done, it will be discarded, and the electric propulsion will kick in and add to this velocity.

The Oberth Powered Maneuver.

The Oberth or Powered Maneuver is an effective option to substantially increase our starships velocity. It is done by performing a dV rocket burn near a planet or star. The velocity provided by a powered maneuver is described by the equation.

EQUATION 0-5 $V = \Delta v\sqrt{1+(\frac{2V_{esc}}{\Delta v})}$

Where:

V= velocity after the powered maneuver and after the vehicle has left the gravity well

Δv= delta v of burn at periapsis

V_{esc}= escape velocity at periapsis

Periapsis is the closest point of our approach to the planet or star. One requirement of a powered maneuver is that to maximize the velocity increase we need to apply our dV as quickly as possible- the quicker the better. For a close dive near a planet, this time will usually be measured in minutes- 15 minutes being a good target. For around a star like the sun, because we can't get as close as we can to a planet (due to the radiation and associated heat as well as its bloated diameter) as well as the fact that the gravitational field is so much larger, we can increase our dV burn time to a couple of hours with a minimal impact to the ideal velocity change. Our engines must be powerful enough and our spacecraft light enough so that the dV can be applied in these short time frames. This means that for a powered maneuver, we are limited to either a high thrust Nuclear Thermal or a chemical rocket. Nuclear Thermal rockets have been an area of active research and development for 70 years and have demonstrated Specific Impulses in the 850sec plus range. It is believed that improved derivatives of these engines may be able to have a specific impulse of 1,000 seconds, or a little over twice that of the LH/LOX SSME derivative.

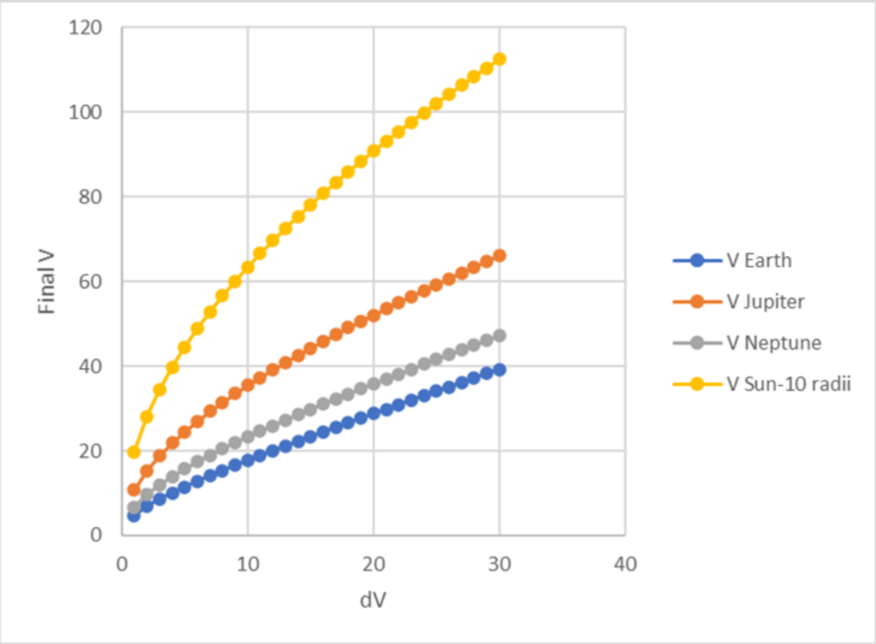


FIGURE 0-3 OBERTH POWERED MANEUVER (NOTE THAT IN THESE CALCULATIONS THE PERIAPSIS DISTANCE FROM THE CENTER OF THE BODY WAS- EARTH- 7000KM; NEPTUNE 28,000KM; JUPITER 75,600KM; SUN 6,757,000KM).

Using a powered maneuver with a dV of 10kps and a close Solar approach to within 10 solar radii would leave us with an impressive velocity of a little over 60kps. At this rate we could reach the nearest star in "only" 22,000 years or so. A voyage this long would indicate a large, crewed starship- it is unlikely that a small uncrewed starship could be built that lasts this long. Extensive maintenance as well as hundreds of nuclear fuel changeouts would be required. Despite 60kps being extremely fast (about 6x greater than our original Saturn V capabilities), 22,000 years is very long, and we would desire to go much faster.

With a two-stage rocket, the first stage would perform a powered maneuver around the sun, and the second stage would continue to accelerate with a low thrust electric propulsion engine. I considered several versions of a two-stage rocket, and settled on one where each stage had a MR of 10. The highest performance obtained with a reasonable payload and structure mass used a Nuclear Thermal (with an specific impulse of 1000 sec) for a first stage powered maneuver around the sun at 10 radii, followed by an electric propulsion engine of 9600 seconds specific impulse. This combination gives us an impressive speed of 300kps. A starship with this performance would be able to get to the nearest star in a bit more than 4300 years, and approach 10 light years in 10,000. With current technology, this is likely the highest feasible velocity.

Even though 300kps is an impressive achievement the two stage rockets leaves several open issues that need to be addressed. The biggest are:

- We want to stop at the target star which means we also have to decelerate from 300kps. With a specific impulse of 10,000 seconds this means we need to increase our starting mass by at least another 20x in order to have mass to decelerate. This will make our m_0 before the sun centered powered maneuver so large that it will make it impossible to achieve the 10kps target for our powered maneuver.
- Since our voyage will be at least 4300 years we need a large vessel baseline starship (m_1). From this we can establish our m_0. We will need to determine a reasonable m_1 before we can determine what our performance requirements (and power requirements) for our propulsion are.

Requirement- Slowing Down at the Target Star

The need to decelerate is problematic. Since our starting m_1 for a crewed mission, a large power supply, engines and interestingly enough, cosmic ray protection for a crewed mission is very large, our m_0 will be huge making the powered maneuver with a dV of 10kps impossible. Furthermore, with the second stage our mass will become so large that our electric propulsion will take thousands of years to accelerate, in some cases so slowly that our ship will not get to 300kps until we are well past our target star. Electric propulsion can provide more substantial thrust but only if the power supply is dramatically increased. Unfortunately, the mass of the power supply will increase linearly with thrust and will quickly consume all of our available m_1 mass.

Solution - Power- Lightweight but High-Power Reactors

The first item to address is designing a lightweight but high power reactor. To date, spacecraft have primarily counted on solar panels or Radioisotope Power Generators (RTG's) to provide power. For an interstellar mission, some form of nuclear power is required but RTG's, while reliable, are very inefficient- converting less than 7% of their thermal heat to electric. The typical RTG provides $4.2w_e$/kg of reactor mass. Furthermore, RTG's typically use plutonium, an artificially created material that is very expensive and highly regulated (due to its ability to make nuclear weapons). No RTG missions have ever created more than about 1000watts of electricity. For larger electric propulsion engines 100kW of power or more are typical. If we had enough plutonium (which we don't) a 100kW electric thrust engine would mass about 29mt.

For a high-power mission fission power is a more viable solution. Fission plants, like those on earth, can generate vast amounts of power and use naturally occurring Uranium 235. The problem is that no fission reactor has ever been built and used in space. The Kilopower Reactor Using Stirling Technology (KRUSTY) was a NASA proposed space nuclear reactor that was to develop 10kw of power from about 44kg of highly enriched Uranium. Its design goal was to generate 6.67W_e/kg or, if converted to Specific Mass as shown in the Figure 0-4, 150kg/kW_e. A smaller demonstration model was successfully tested in 2017.

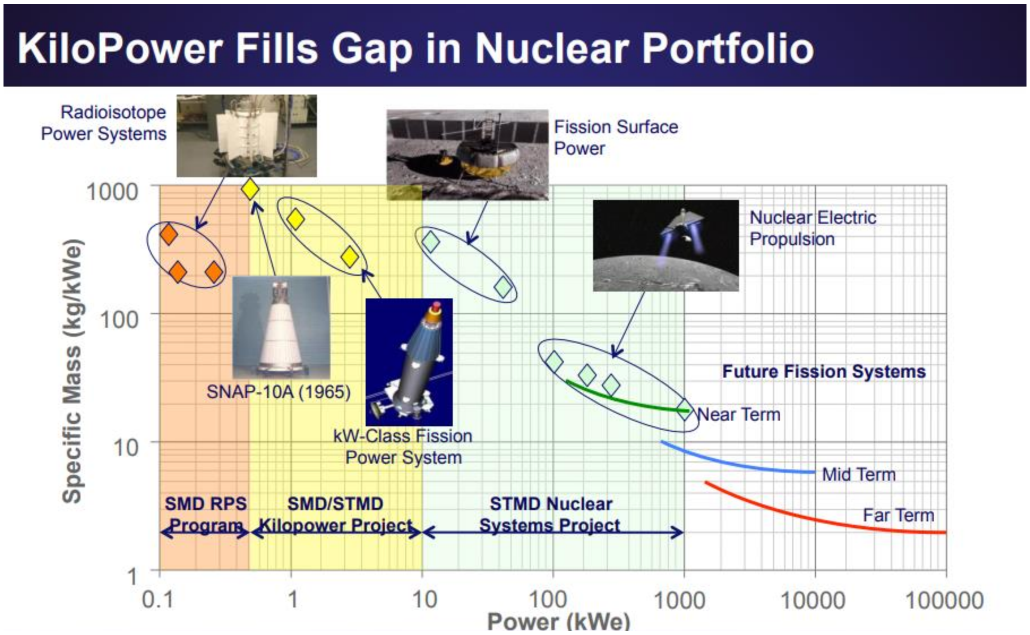
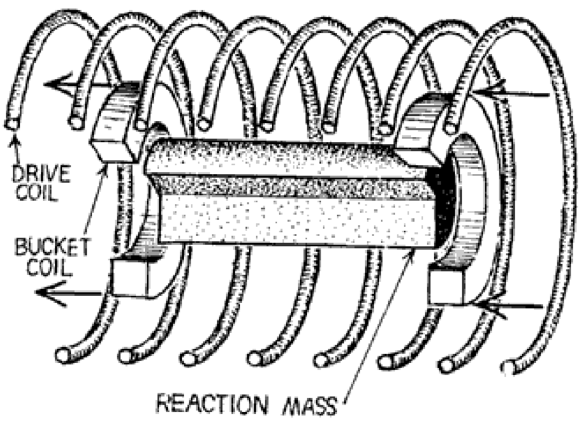


FIGURE 0-4 NUCLEAR TECHNOLOGY (COURTESY OF NASA)

How large a thrust is needed is determined by how massive our starship is, so to calculate the minimal acceptable Specific Mass for our power system that will enable our mission is an iterative process where the variables are adjusted. By running various scenarios, I determined that the bare minimum requirement is power plants at least 3x more mass efficient than the KRUSTY design, or 20W_e/kg or a Specific Mass of 50kg/kWe. If our power plant puts out less than this, we quickly wind up dedicating all our spacecraft m_1 mass to the power plant and have nothing available for anything else (habitation module, fuel tanks) etc.



Solution - Changing the Mission Architecture-Enroute Mass Supply

Even with a relatively lightweight but high-power reactor, the MR of 400 is an insurmountable obstacle. Up to this point it seems as if a viable starship is impossible with current technology (unless we decrease our speed substantially – perhaps to 150kps and a 9000 year mission). There is no way of developing a reasonably starship without radically rethinking our mission architecture.

FIGURE 0-5 SIMPLIFIED MASS DRIVER OPERATION (KOLM, 1980)

In 1979 Clifford E Singer made a speculative proposal to launch millions of pellets with a large mass driver (Singer, 1979). A mass driver is similar to an electric propulsion thruster except it accelerates buckets filled with a mass/payload instead of individual ions. The pellets would impact the starships absorption plate and would impart their momentum to our rocket.

In Singers design the following was proposed:

- A mission to Barnards Star traveling at .12c (36,000kps)
- Pellets would be from 3-100 grams. For this scenario he picked a pellet 2.8grams
- Accelerator would be 10^5 km long
- Acceleration of pellets would be on the order of .3 to 4 mega gravities (300,000 to 4 million g)
- For a 2.8 gram pellet, a 15 GW Power source was required over 3 years
- Two pellets would be launched each second at .25c (75,000 kps)

The challenges of building this sort of propulsion device are substantial. In short:

- Accuracy of the pellet and vehicle trajectory. Singer proposed that a dozen correcting stations be positioned 340 AU apart to ensure the pellets were accurately targeted.
- The tremendous speed of pellets leads to the requirements for a massive pellet launcher.
- The tremendous speed of the pellets requires a tremendous power supply.
- The tremendous speed of the pellets requires huge acceleration. Would we even be able to accelerate a pellet this quickly with electromagnetic means? Particle accelerators can but they are dealing with individual atoms.

Despite these challenges, the pellet proposal has considerable merit.

- It transfers all the reaction mass to the pellets being launched from the solar system. His starship would carry no fuel/reaction mass (unless it needs to slow down at the target star). This means that our starship consists essentially of structure and payload only. Not having to waste most of your mass and therefore energy accelerating your dead fuel mass reduces the amount of mass needed substantially.
- Even though the amount of power needed to launch your pellets is substantial, it transfers most of the power needed to the Solar System where it can be generated far easier via Nuclear or Solar power. The ship does not need any power for propulsion.
- It is more efficient than a large laser accelerating a solar sail. Between laser efficiency issues and the dispersion of laser light over large distances, typically less than 5% of the power generated would go to propelling a solar sail spaceship.

By developing a far less ambitious version of this can we adapt it to our needs?

Packet resupply

How would such a mission work? As before we build a two stage ship whose first stage does a solar powered maneuver. This would put the starship on a hyperbolic escape trajectory toward our star. In the case of a dV of 10kps and a 10 radii solar approach we would achieve a velocity of just over 60kps, and if we performed the same maneuver at 3 solar radii our speed would be an impressive 85kps.

At this stage, instead of using stored mass on our starship to continue our acceleration, we instead start picking up mass via “packets” that are lying in our starship path (or conversely, these mass packets catch up and are picked up from behind the starship). These packets would be then used as the reaction mass for our rocket. As with a jet engine, effectively NO reaction mass would be carried as the ship accelerates to 300kps. After this stage the starship would continue to pick up these packets but instead of using them to accelerate, we would use this mass to build up our cosmic ray protection, refuel our reactors, replace any consumables, and start accumulating reaction mass for our deceleration.

These packets would have been launched from a large asteroid based mass driver (henceforth called the Mega Mass Driver or MMD). The specifications for this mass driver will be impressive but much less challenging that which was proposed by Singer. Our MMD would have the following specifications:

- Launch 20kg packets- half of this mass will consist of the accelerating bucket, electronics, solar panels and small ion engines, and the other half would be payload
- Launch at speeds up to 300kps
- Accelerate packets at 10,000g
- MMD will be approximately 440km long
- Launch at rapid fire rate-depending on the design and starship velocity up to 95 packets per second

One characteristic of the launcher packet is that each packet will be 50% payload, and 50% bucket/spacecraft. The bucket/spacecraft will generate the magnetic field necessary to permit the packet be accelerated at 10000g and after launch, receive power from solar panels illuminated by a laser beam. The purpose of these solar panels is receiving laser light to power electronics and sensors that would accurately track the packet and its relation to the packet in front of it. Over the first day or two of its journey, very small electric propulsion thruster will be used to fine tune its position so that the two packets will drift very little in the course of many years – with a target of no more than a meter or two per year. All this adjustment would be done when the packet is still relatively close to the MMD and being illuminated by a laser beam. Whether this level of trajectory accuracy is possible is highly speculative and considerable engineering and analysis would need to be performed. The method by which the packets would be captured by our starship would strongly constrain the acceptable rate of drift between packets. I would conceive of our starship having multiple capture nets by which a recovery net attached by a long cable to the ship would be fired at the approaching packet. The nets would capture the payload and then be reeled in to be processed for either propulsion or to build up our starship (primarily cosmic ray protection at the beginning of the mission, followed by accumulating reaction mass for the eventual deceleration, but also some replacement raw materials such as Uranium for the power generation).

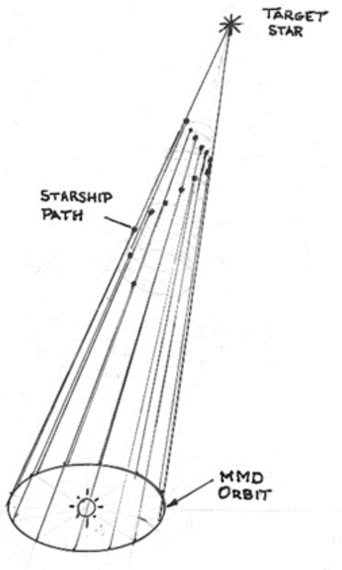


Figure 0-6 Notional Starship Flight Profile and MMD Packet Trajectory

Note that with this scheme the packet consists of a bucket and spacecraft. Mass drivers have been considered before (primarily as a means to launch raw materials from a moon or asteroid without the need for a rocket) but in these scenarios, the bucket was kept and reused - it was decelerated after it had accelerated and released its payload. This may turn out to be necessary, but this will add considerable length and mass to our MMD since the buckets will now have to be decelerated and cycled back down to their starting point.

Finally, whether the starship runs into the packets as it cruises along, or the packets catch up with the starship and are picked up, would have to be decided based on an analysis that weighs the positive and negatives of each method. Figure 0-8 is a notional starship design that assumes packets are approaching from the rear.

Selecting the Propulsion- Electric Propulsion or Mass Driver for our Starship?

We need a specific impulse for our starship of around 10,000 seconds if we are to get close to 300kps. The packets will provide the reaction mass to complete our acceleration and enable our deceleration. As such, if a form of electric propulsion is used, the packet "payload" will likely be one of the typical reaction masses used by ion or plasma propulsion- a noble gas. This means that likely less than half the 20kg packet mass is used – or 10kg, assuming the other 10kg is for our bucket, electronics, solar panels and ion engines and our noble gas (likely chilled to a liquid) container.

An alternative to using electric propulsion is the same technology used for our MMD- a smaller mass driver to propel our starship. The performance of this mass driver (we will call this one the MD) will be much less than what was required for the MMD- the exhaust velocity for a specific impulse of 10,000 combined with a 10,000 g acceleration would require a driver length of "only" 49km. How much would an MD of this size mass? Since a large mass driver has never been built, it is difficult to determine. Depending on the size the Starship mass packets are (I decided we would use a smaller mass of 1kg per launch) the buckets will be quite small- likely only a few cm in diameter. If the MD support structure is aluminum the mass could be quite low- I estimate about 500kg per meter. For reference, I found an article that stated that a large radio tower in North Dakota made of steel masses 392,131kg which converts to about 660kg per meter. The base of this tower has to support 392mt which equates to 3.9 million nt which does not even include the forces caused by wind loads. Our MD should have force only a fraction of this- if we accelerate a 1kg payload at 10000 g the force would be about 100,000nt. For a first estimate, I think 500kg per meter may not be unreasonable. Using this mass our MD will mass about 25,000mt.

We need to determine which will be a better source of thrust- electric propulsion or MD? I ran several analyses, and it turns out that unless our starship is very small, it is more effective to go with a mass driver. With electric propulsion doubling your thrust will double your propulsion mass. With an MD, the thrust is periodic… for argument's sake let's say every ten seconds. You can double your thrust by firing every five seconds and the mass of your MD will not increase.

However, the biggest advantage of using a MD is that I assumed that we can use all the supplied packet mass for reaction mass, reducing the number of packets by 50% over using an electric propulsion. This also applies to the mass collected for deceleration. For each packet delivered if using an electric propulsion, only about 50% would be useable for reaction mass.

The third minor advantage to using an MD is likely to be the electric conversion efficiency- electric propulsion typically achieve a conversion efficiency of electric power to thrust of 50%. The mass driver estimates may approach 80% (Kolm, 1980).

Requirement - How big does our ship need to be for a 4,300 year mission?

The effectiveness and applicability of the above proposed solutions depend to a great extent on how big our starship will be. A starship that starts out as a two-stage vessel that counts on a powered maneuver may have an m_1 mass that is so large the ship will need an unreasonable amount of engines and unrealistically large amount of reaction mass to perform the maneuver. The same applies to our ship once it is coasting. The number of packets needed, the size of our power supply, and the selection of the engine type will all be effected by our coasting mass. Finally, our deceleration is fixed at a MR of 20 so the ending mass of our starship needs to be known to calculate how much mass will have to be supplied by packet resupply.

Size and Mass of Crew Tori

Since our voyage will last thousands of years a crewed mission is required that can be viable for hundreds of generations. There have been many studies done that have attempted to determine the minimal size needed to have a multi-generational population. These studies have indicated anywhere from a few dozen to ten's of thousands. I decided to pick a crew size of 1000. This size, combined with frozen embryo's and sperm should ensure sufficient genetic diversity and enough resources to maintain the ship. I then looked at how large the ship would need to be to support this population for hundreds of generations.

In the 1970's Gerard K O'Neil pulled together a team to develop a space settlement plan (Johnson & Holbrow, 1977). In this study, it was estimated that about 10 acres of intensively cultivated land could support every 1000 people (Heppenheimer, 1977, p. 128). I believe that with genetically modified organisms, hydroponics, and additional improvements in farming including growing of artificial meat (eliminating the need for cows, pigs, etc.) we may be able to double this productivity. Using this rule of thumb, we will need 20,000 m^2 of land which equates to about 5acres dedicated to farming/food to feed the colonists. Some additional area would need to be set aside for housing, offices and manufacturing.

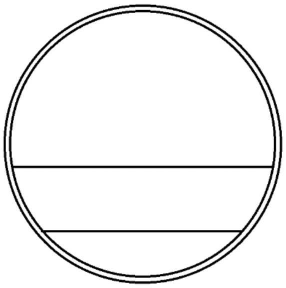


FIGURE 0-7 TORUS CROSS SECTION

The same Space Settlement study also determined that the most efficient structure for a small or medium sized colony was the torus. Using a double deck configuration (Figure 0-7), and adding some land for offices, public spaces, and apartments, the minimal size that would be viable is one with a minor diameter of 15m which gives almost 28,000m^2 on two decks. I also used a major diameter of 204 meters to give a gravity of .9 earth normal at 2 rpm. By calculating the mass of the structure including deadweight, we could build a torus structure of about 17,000mt. Adding additional mass as a margin of error, and including water and soil for crops 19,000 mt would be more likely. For stability, a second counter rotating torus would be added to bring the total mass of the two tori to 38,000mt. One of the tori would be for habitation and include farm land. The second torus would serve as storage for supplies as well as contain some of our power (reactors).

Mass of Power Supply

To this we would add the MD propulsion (which we already estimated to be 25,000 mt) and power supply. I considered several iterations of a starship attempting to balance mass flow of our mass driver, with a the mass of the power supply and finally settled on a one kg mass being accelerated every 5.25seconds (equivalent of .19kg per second). To accelerate this mass, assuming a MD efficiency of 80%, requires a power plant of about 1.2GW. Using the design target of the power plant generating 20 W_e/kg our powerplant(s) will mass 60,000mt. Note that if we develop an even higher power lightweight reactor, it would permit a considerable improvement to our design with either a faster ship acceleration (because the ship is lighter, or because we have more power to generate more thrust) or allow us to have a larger habitat and more cosmic radiation protection.

Mass of Cosmic Ray Protection

One striking aspect about building a starship is the amount of mass needed for passive cosmic ray protection- this exceeds by far our tori, powerplants, and MD. Literature indicates that the best materials are polyethylene type material or water from 6 to 7 meters thick (Globus). It turns out that to wrap a single torus with a minor diameter of 15m (with a one-meter standoff distance) with 6meters of water would mass about 550.000mt. If we use this amount of mass for our starship during our powered maneuver our mass is too large to perform a 10kps dV in the short amount of time we have allocated.

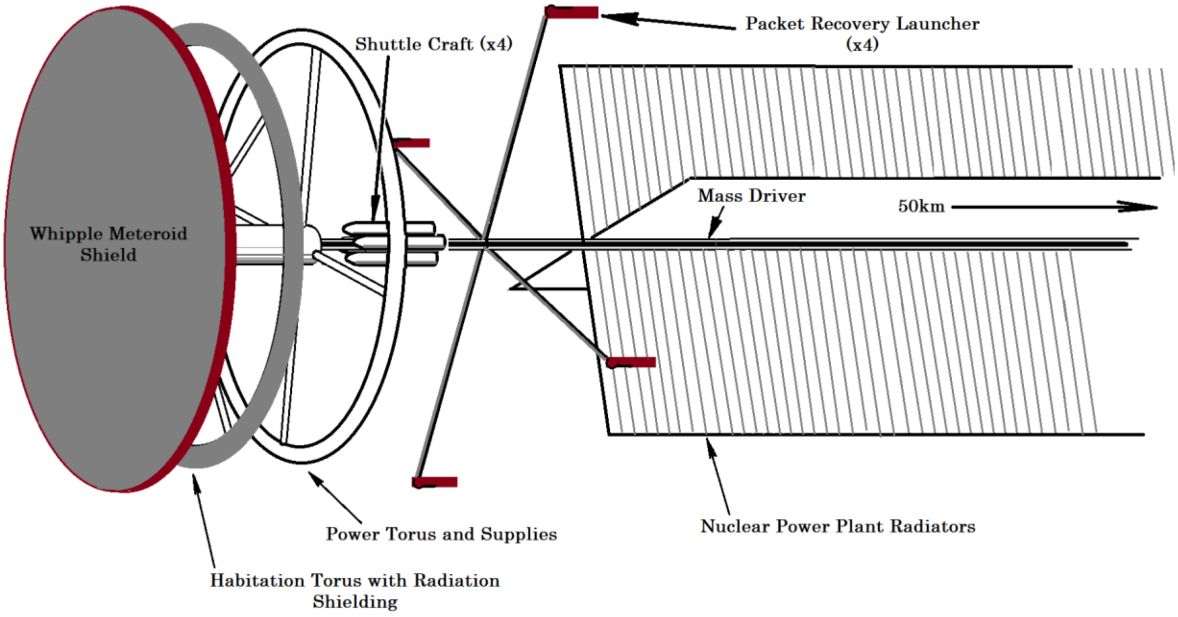


Figure 0-8 Notional Starship Layout

I looked at several scenarios for a 10kps dV maneuver during a 2-hour closest approach to the sun. Using Nuclear Engines with a specific impulse of 1000seconds we would start out with a mass around 582,000mt and end with a mass of 210,000mt. If we elected to use a LH/LOX engine similar to the SSME our m_0 would be very large- just shy of 2 million mt- difficult but not impossible- we would need the equivalent of 116 SSME engines firing for two hours. Using the 210,000mt as our target m_1 mass after the powered maneuver, and after allocating mass for our habitat, power supply, and mass driver, we would be left with about 85,000mt for our cosmic ray protection. While 85,000mt is substantial, it would only equate to a little over a meter in protection. This would not be adequate for a multigenerational ship.

This is where our packet resupply can come in… our packets can provide material (likely water) for us to build up our cosmic ray protection. The ship would continuously pick up packets over the period of several centuries and build out our cosmic ray protection, replace spent fuel, install meteoroid protection etc.

When the fully assembled starship is considered, we have the following:

	Mass mt	Velocity	
Mission Start	582,000		At star of powered maneuver. Assume Nuclear Thermal Engine with 1000 Isp engine
End of Powered Maneuver	210,000	65	After 10 radii solar approach
Acceleration Phase	200,000	300	After powered maneuver, dispose of sun shield, unneeded engines. Reaction mass starts getting picked up. Assume Mass Driver of 10,000 Isp
Coast	4,000,000	300	Build up Cosmic Ray Protection and meteoroid shield
Decelerate	200,000	0	Target Star Arrival

TABLE 0-1

A more detailed analysis indicates that the acceleration period is still substantial- 73 years- assuming we don't add more mass to our minimal cosmic ray protection until after the acceleration is complete. At the end of our 73 years we would start adding to our cosmic ray protection around the torus, and after this is complete, the additional mass would be placed in front of the starship where it will serve as a meteoroid barrier. To collect the 3.8million mt mass to build out of full starship will take on the order of 650 years. The logistics of such a starship are daunting.

Areas for Engineering Improvements

Even though I tried keeping the technology as conservative as possible, there would need to be considerable engineering work to verify this mission architecture is possible. Some of the key technologies required:

- Developing high powered but lightweight fission reactors able to generate at least 20W/kg
- Develop the technology to accelerate buckets and payload at 10,000g with a large MMD
- Develop the packet spacecraft, propulsion and guidance system to ensure accurate target positioning.
- Develop a lightweight MD for our starship that can accelerate a 1kg packet at 10000g. Target mass goal for the MD would be 500kg per meter.

The industrial requirements are even more substantial. The largest are:

- Design and build a very large 440km MMD
- Develop space-based manufacturing capabilities to build our starship and the MMD
- Develop vary large power storage system to power the MMD. Depending on the final design (mass of packets, mass of ship, speed of approach to the ship) as well as the velocity of the starship the MMD may be sending out up to 95 packets per second! Note that this high rate is primarily driven by the desire to have the packets approach the ship at no more than 30mps. If we were to double the approach rate to 60mps our MMD would only need to launch every 42.5 packets per second which would also reduce our instantaneous power consumption by 50% (though total power required would still be the same- it would just double the MMD launch period). When the MMD is launching at peak rate of 95packets per second, it will need 86TJ which is more than all the electricity generated on the earth. However, at the rate of 95 packets per second this large amount of power would only be needed for slightly less than a month.
- Develop manufacturing capabilities for mass production of our buckets. An analysis of the need to accelerate up to 300kps and then to build out our starship to a final m_0 mass of 4 million mt indicates we will require a total of about 215 million packets of 20kg each. If our starship does not use an MMD and instead uses an electric propulsion with a payload of a noble gas, then the number of packets will approximately double.

The two technologies that could dramatically change our mission profile and perhaps simplify any starship design are Solar Sails and an advanced Nuclear Engine- either an advanced fission rocket or a fusion powered one. Because of the unknowns associated with their feasibility, I did not include these in my starship design. If extremely lightweight but strong materials could be made then Solar Sails would drastically modify our mission. Launching millions of small solar sails that carry a small payload could eliminate the need for a large MMD and its associated power supply. Similarly, powerful, relatively lightweight fusion power could eliminate the need for our Starship MD. The fusion reactions could be used to generate both power and thrust. Hopefully over the next few decades both technologies will advance enough that a revised starship design can be considered.

Conclusion

It appears technically feasible to build a starship without any fundamental new technologies though it would be extremely difficult. If designed now, the starship would have the following characteristics:

- A two-stage configuration, the first a high thrust engine to perform a powered maneuver to reach a solar system escape velocity, and the second a lower thrust mass driver.
- A 300kps top speed
- The power supply onboard the starship will have to provide at least $20W_e$/kg and it would need to supply about $1.2GW_e$
- Enroute packet resupply will be needed both to provide reaction mass for our outbound stage 2 acceleration, as well as material to build out our cosmic ray protection, providing some resupply including fuel for our nuclear reactors) and build up the mass for our eventual deceleration.
- An m_1 mass of about 200,000 mt for a crew of 1000 and an m_0 mass of about 4million mt.

With all these characteristics, our starship would still require a voyage time of over 4300 years.

Despite the possible technical feasibility, the space based industrial requirements are substantial and will not exist for many decades. This article only covers some of the highlights and further details, along with many additional challenges that were not addressed here are discussed on my website https://www.allthingsspace.info.

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