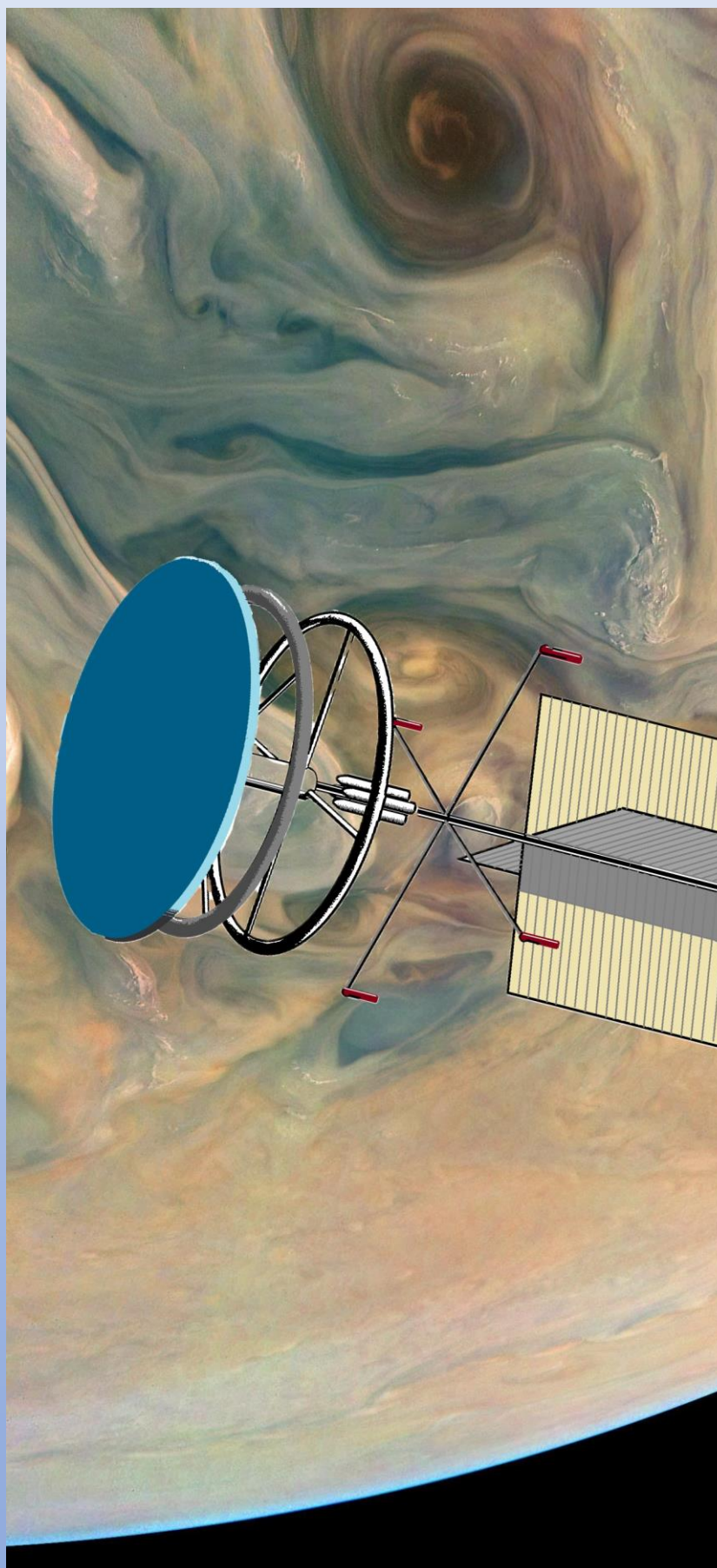




Building a Starship in the 21st Century

August 2024

David W McGuire

Contents

Contents.....	1
Preface	9
Chapter 1- The Solar System and Beyond.....	12
Space is Vast.....	12
Space is Empty	16
Space is Massive and Resource Rich	17
The Nearest Stars- Where would we go?	20
Habitable Zones	27
Chapter 2- Orbits.....	29
Gravity and Orbital Mechanics	29
Newtons Laws	29
Characteristics of Orbits.....	30
Circular Orbits	32
Ellipses and Hohmann Transfer Orbit	33
Escape Velocity	36
Faster than Escape Velocity	37
Gravitational Slingshot.....	37
Oberth Effect or Powered Maneuver	41
Chapter 3- Rockets and the Rocket Equation	45
Rockets.....	45
Rocket Equation	46
The Advantages of Staging.....	48
The Tyranny of the Rocket Equation.....	49
Rocket Design in Real Life	51
Friction with the atmosphere:	51
Gravity Loss	54
Engine Efficiency Considerations	54
Chapter 4- Surviving in Space- History and Economics.....	60
History- the Story Until Now	60
Economics	61
Launch Costs	63
Resource Availability.....	66

Making Space Habitable	71
Artificial Gravity	72
Meteoroids.....	75
Cosmic Radiation.....	76
Chapter 5- Saturn V and Skylab- 2030's.....	79
Stage 1.....	82
Stage 2.....	83
Stage 3.....	83
Mission.....	84
Saturn VA- Apollo design	85
Saturn VB- Skylab	86
Water, Oxygen and Food	86
Technology- Power- Fuel Cells and Solar.....	87
Solar Panels.....	88
Fuel Cells	88
Cost	90
Summary and Conclusions	92
Chapter 6- Saturn VI and SpaceX Starship- 2040's	93
Space X Starship	94
Physics of Fuel and Oxidizer.....	98
Technology- Power- Radioisotope Thermoelectric Generator	100
Technology- Communications and Raleigh's Criteria	104
Saturn VIA	107
Launching from the Lagrangian point.....	115
Gravitational Slingshot.....	116
Tank Material Selection	116
Unmanned	116
Manned.....	117
Cost	118
Summary and Conclusions	120
Chapter 7- Saturn VII- 2050's.....	123
Technology- Nuclear Thermal.....	123
The Powered Maneuver	125

Saturn VIIA	126
Technology- Electrically Powered Spacecraft Propulsion	128
Hall Effect thrusters.	129
NSTAR- (Nasa Solar Technology Application Readiness)	130
NEXT- (NASA Evolutionary Xenon Thruster)	130
HiPEP (High Power Electrical Propulsion)	131
Magnetoplasmadynamic (MPD) thruster (MPDT)-.....	131
Variable Specific Impulse Magnetoplasma Rocket – (VASIMR)	132
Summary of Electric Thruster Capabilities.....	132
Technology- Power Options.....	135
Ways of Generating Power	136
Generating it for Centuries	137
Summary of Nuclear Power Options	138
Saturn VIIB- Electric Thruster	141
Saturn VIIC- Two Stage Hybrid	143
Cost	145
Summary and Conclusions	147
Chapter 8- Saturn VIII- 2060's	149
Saturn VIIIA- Nuclear Thermal improved and the Power Maneuver.....	149
Solar Heating During an Aggressive Powered Maneuver	151
Technology- Solar Thermal	157
Technology- Power- Fission Reactors	157
Saturn VIIIB- Electrical Thrusters Improved.....	162
Saturn VIIC- Two Stage Hybrid	165
Cost	166
Summary and Conclusions	167
Chapter 9- Saturn IX- 2070's	169
Saturn IXA- Electric Thruster with beamed power	170
Saturn IXB- The Extreme Beamed Version.....	171
Laser Beamed Power- Making this Work.....	172
Saturn IXC- Solar Sailing	174
Case 1- Solar Sail Thrust is less than the local gravity.....	177
Case 2 Solar Sail thrust equals local Gravitational Force	179

Case 3- Solar Sail thrust equals twice the local Gravitational Force	180
Laser Beamed Thrust for Solar Sails	185
Saturn IXD- Mass Driver	187
Pellet Propelled	193
Technology- Power Supply- Fission	196
Summary and Conclusions	197
Chapter 10- Saturn X- 2080's- Developing a New Mission Profile	199
A Note on Deceleration	200
Saturn XA - Electric Engine	201
Power Requirements	202
Acceleration Challenges	203
Saturn XB- Collecting Mass Enroute	204
Deceleration on Arrival	206
Saturn XC- Three Stage Hybrid	207
Summary and Conclusions	211
Chapter 11- Designing and Building- 2080's	213
Comparison of Electric vs Mass Driver on deceleration	213
Mega Mass Driver (MMD)	218
MMD Power Supply	219
Packets- Design, Targeting and Production	219
Mass produced Solar Sails	222
Building enroute	222
Summary and Conclusions	224
Chapter 12- Saturn C- 2090's	226
Saturn C	227
Habitat	227
Calculating Mass of our Starship	243
Summary and Conclusions	254
Chapter 13- Phase 1-3: The First 13 Years	256
Phase 1- Asteroid Colonizing Ships Alpha- Delta- Years 0-4- Launching from Earth	257
Phase 2- Years 5-8- Asteroid Construction and Fuel Generation	261
Mining and Material Separation	262
Torii Construction	263

Tank Construction	266
Engine Placement.....	267
Waste and Slag Disposal	268
Mass Driver Construction	268
Sun Shield Construction	268
Power Supply Construction.....	269
Phase 3- Years 9-13- Sundiver	270
Nerva+ Option.....	271
LH/LOX Option	272
Disposal of unneeded mass	275
Summary and Conclusions.....	275
Chapter 14- Phase 4/5: Years 14-721	277
Phase 4: Years 14-87- Acceleration Phase	277
Phase 5- Years 87-721 Expansion and Build Out	279
Whipple Shield	282
Supplies	283
Recycling	284
Summary and Conclusions.....	287
Chapter 15- Years 722-10,000- Phase 6/7/8 Cruise, Deceleration and Colonization	288
Phase 6- Cruise- Years 722-9000.....	289
Manufacturing and Fabrication	289
Sheet metal:.....	289
Foundry	289
Manufacture of pipe:	289
Machined Parts:	289
Manufacture of Rubber and Composites:.....	290
Lighting:.....	290
Computer components and electronics:	290
Complicated Machine and Robot Repair:	290
Food Production.....	290
The Human Factors	291
Living in a torus	292
Phase 7- Deceleration- Years 9000-9634	295

Phase 8- Colonizing- Years 9634-?	295
Landing craft	296
Summary and Conclusions	298
Chapter 16- Back in Our Solar System	300
Selecting the Star	301
Building a Telescope	301
Developing our Power Supply	303
Fission.....	303
Fusion.....	304
Raw Materials and Mining	304
Building and Manufacturing Technology.....	307
Building the Colony Ships.....	308
Building the MMD.....	309
Starship Acceleration and Resupply.....	313
Summary of Material Requirements	313
Summary and Conclusions.....	318
Chapter 17- Future Technologies and Speculation.....	320
Power and Propulsion Technologies.....	321
Lightweight Fission Reactors.....	321
Liquid and Gaseous Fission Rockets.....	321
Fusion Rocket.....	322
Solar Sailing	323
Project Orion and Daedalus	323
Thinking Way Out of the Box	324
Metallic Hydrogen.....	325
Momentum Transfer (MT)	325
Photon Rocket.....	328
Antimatter Rocket.....	329
Artificial Womb	330
Suspended Animation	331
The Ideal Interstellar Spacecraft.....	332
Technology Review, Potential and Maturity.....	332
Summary and Conclusions	335

Chapter 18- Conclusions	337
Summary of Methods	337
Why should we go?	338
Diversity minimizes the chance for extinction.....	339
Where are they?	343
Expansion prevents stagnation.....	345
Summary and Conclusions.....	348
Appendixes.....	350
Appendix A- Scientific Notation, Conversion Factors	350
Appendix B- The Nearest Stars- Out to 16 LY	351
Appendix C- Selected Space Probes and Interstellar Spacecraft	354
Appendix D- Some Physical Constants and Properties	355
Appendix E- Properties of the Planets	356
Appendix F- Summary of Design	357
Appendix G- Suggested Further Reading	358
Bibliography	359

This book is dedicated to Cathy, my wife and partner in life for 30+ years. Because of you, every day is a gift, and I am eternally grateful for every moment.

Preface

Most film aficionados have heard the story that Alfred Hitchcock's working title for his famous movie "North by Northwest" was "The Man in Lincoln's Nose". Fortunately, he did not stick with that title. Similarly, my working title when authoring this book was "Saturn to the Stars: Building a Starship for the 21st Century". My wife said that was title was not so great. I suspect she is right... but that does not mean that I am not fond of the original name- for this is how this book got started. I wondered what we could do if we put a fully loaded Saturn V in orbit around the earth and said "GO". When I first started thinking of this book it was over five years ago. By the time I got around to writing it and finishing the first drafts, Saturn V was looking long of tooth and out of date... the SpaceX Starship is now conducting test flights and is far larger than the Saturn V. For this reason, I changed the title and updated the text to bring it up to speed.

The goal of this book remains unchanged... I wanted to see what it takes to build a starship- not in the distant future but "now". Stretching the definition of "now" a bit I want to be able to launch it this century so that people alive today can either help with its building or participate in the voyage.

When anyone first starts thinking about traveling to the stars, they usually ask themselves how hard is it really? As you probably can already guess, it is hard- really hard. Like others have done, I had read several books on the subject but still found it hard to imagine how daunting the task is. Frequently non-fiction books quickly jumped into the realm of Einstein time dilation effects and wormholes for interstellar travel. While it may come to pass that some of these things can be built, I am skeptical. The physics is too speculative, and the energy requirements are frequently "astronomical". Most of these books are excellent, but they approach it from a "physics" point of view- they count on things that are theoretically possible, but not what has been or can with only modest extrapolation, be reasonably built. Instead of a "scientist" point of view, I wanted to approach this more from an "engineers'" point of view.

In this book I ask a basic question- could we build a starship using only known science and engineering principles and if so, how? I took Elon Musk for part of my inspiration. He took "old" knowledge and rethought the problem of launching rockets into space and developed a whole new, and cheaper way of getting into space. Anyone who has seen a Falcon 9 first stage returning to its pad with pinpoint accuracy can't fail but be impressed. But even more important, I found myself asking, why didn't any of the rocket companies that have been building rockets for, in some cases over half a century, come up with these ideas? Partly it is because of a lack of vision. If the government was not going to pay for the development of a reusable first stage, they certainly weren't. SpaceX had a vision. And because they were going to develop it (mostly) with their own money, they needed to stay laser focused and passionate. Musk did not come up with any fundamental new technology- but he did take known technology, added a lot more computer power, a factory focused mass production philosophy all while focused on how to make spaceflight cheaper.

Another goal I set out is to make this book "approachable". I made a conscious effort to straddle the line between an overly simple non-technical approach and a college level textbook. I wanted this book to be fun. It is not a college textbook and advanced math is most certainly not needed. To appreciate the vastness of the universe, the limitations of rockets, the huge amounts of power required, and the

technical challenges of building a starship, math is required. In most cases I have not derived the math- this was left to other, smarter people (and longer books). But I did want to give the basic math tools so people can better understand the challenges, as well as, if they choose, be able to apply the math themselves and perhaps come up with something no one else has thought of.

All books need to start somewhere, and I chose to begin with my simple question- what if we could magically lift a fully fueled Saturn V into orbit and launch from there? Up until 2024 the Saturn V was the largest, heaviest, and most powerful rocket ever launched. If we could place a Saturn V in orbit and launch from there how fast would we travel? How long would it take to get to the nearest stars? What could our payload be? I also looked at the capabilities the even larger SpaceX Starship could bring.

In each chapter I introduce incremental technological improvements and improved successive iterations. I could have taken a different approach and dedicated each chapter to a specific engineering problem- as in having a chapter on various rocket propulsion options and another one on power sources. However, rockets are a system and must be designed as such. The choice of propulsion will drive various other engineering decisions and design compromises. In this way we can progressively improve our whole vehicle to its end goal- a viable starship.

These basic ideas and requirements help determine the constraints of our starship-

- It has to be able to be built and launched in the 21st century. This caveat drives several large “sub” restrictions:
 - o It must be technologically feasible. Because of this we will not be discussing warp drives or buzzard ramjets. It must be built with our current technology or a reasonable extrapolation of it.
 - o In keeping with building the starship “now”, it must be practical to build. No huge space industry to support. No mining the atmosphere of Jupiter. Being practical means being affordable. It can’t use up the GDP of the planet or even of a nation. That does not mean it will be cheap. This project could reasonably cost 10-20 billion a year – in most cases spread out over a few decades. That is still a lot of money but in alignment with some large defense contracts. For instance, the procurement budget for the F-35 fighter program is estimated to be in the \$400 billion range, spread out over a couple of decades. This is certainly a doable sum for large nations or even large companies.
- We need to determine our targets- in other words we need to determine how far it will need to travel. Without this constraint it is hard to determine what the design needs to be. Some stars are relatively close- a few light years- but most stars are much further. We need to choose a reasonable target.
- Have a purpose. This means either able to do useful science, or, in later iterations, colonize. We will consider both manned and unmanned starships and will eventually work our way up to a colony ship.

As engineers and Project Managers know large projects seem to always cost more and take longer than planned. Why do so many large projects have large cost increases and schedule slips? The primary drivers of this are design unknowns, complexity, and underestimation of the logistic challenges (which is usually related to complexity). My desire to launch this century and keep the ship practical is what is driving me to establish the rule of technological feasibility. Certainly, we can improve on our technology, but this will likely be both more costly and take longer than expected. An example of this is fusion

power. In the 1950's it seemed that fusion power was only 30 or so years away. As it turned out, having controlled and practical fusion reactors has been much more difficult than originally anticipated. After 60 years of progress, practical fusion is still forecast to be about 30 years away. This leads to the oft heard variant of the joke- "fusion is the power of the future, and always will be". To avoid this paralysis, I have the rule that the starship design has to be technological feasibility.

But even if the technology is conservative, projects can take much longer and cost far more than anticipated. Not only does the unpredictability of technological advances trip up many optimistic forecasts, but logistics, the science of moving the people and mobilizing the resources to actually build the project frequently is the victim of excessive optimism. The larger and more complicated a project is the more schedule risk arises because of logistics bottlenecks- hundreds or even millions of things must occur in a proper sequence to support the project. To name but a few of the problems that always occur on large projects we have equipment breakdowns, weather challenges, or supplies not arriving on time. There are several ways to handle risk and mitigate the impacts of problems- including adding cushion in your schedule, detailed planning, and the tried-and-true solution- spend more money (another way of saying throw more resources at the problems). Finally, there is the ultimate solution when all else fails, extend the project deadline. However, when all is said and done the simplest solution to reducing program risk is to keep your project as small (and simple) as possible. This ties into the second "sub" rule- it has to be practical.

The next consideration is selecting our target. In this book, we have established that the mission will be interstellar. Some stars are substantially closer than others. Also, some stars will not make good targets. Some may have no planets, or the star too small, or variable, to make them a pleasant place to colonize. The target stars, their distance, and their local conditions will drive our design and colonizing parameters.

The final consideration is that the mission must have a purpose. It needs to either do science, colonize or both. Throughout this book I will address the ships' capabilities and payloads and the limits that they impose to accomplish their purpose.

I wrote this book for fun. It does not require advanced math skills. When I started writing it, I primarily wanted to learn about interstellar travel- what its challenges were and what capabilities we might develop to overcome them. In many ways this book represents my thought process- and, to some extent, a detective story. It starts with getting familiar with the basics of rockets, looks at current capabilities, looks at the challenges and solutions and in the process introduces more and more capable "starships" and their systems. Every time a problem comes up, I look at several solutions, their positives and negatives, the risks, the rewards and finally pick an apparent best direction forward. Occasionally some of the things I look at, like in any good detective story, are dead ends and false leads. But like any detective story, I try to have a satisfying conclusion. I hope you enjoy the engineering and science challenges encountered along the way.

Let's get started!

Chapter 1- The Solar System and Beyond

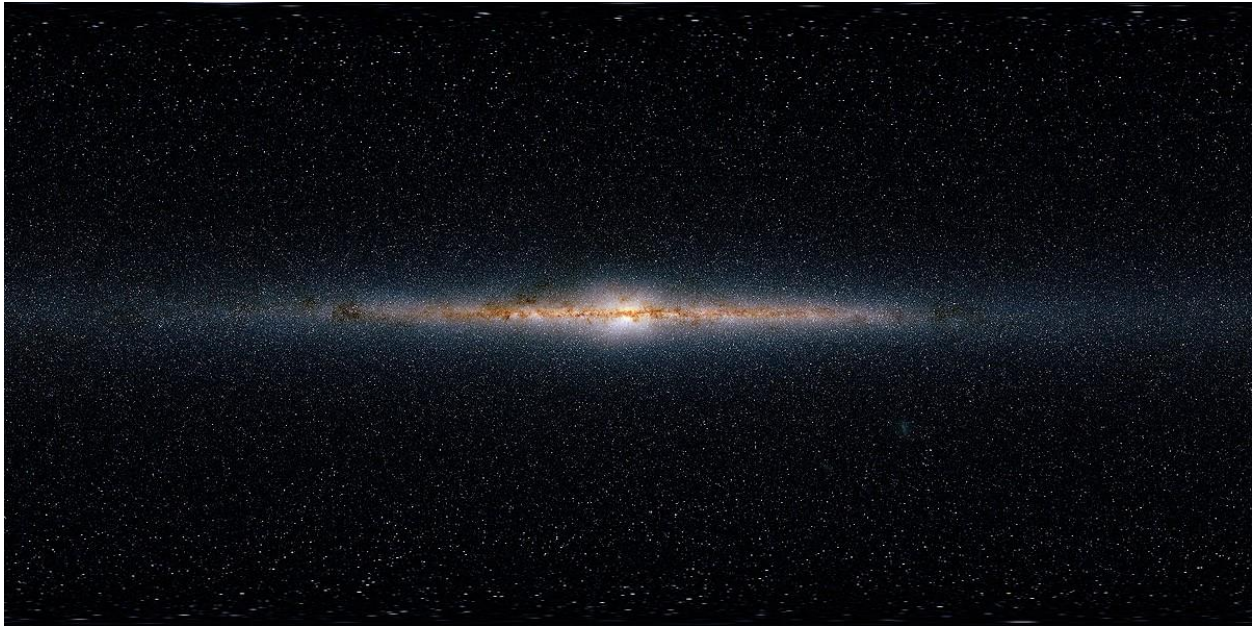


FIGURE 1-1 OUR MILKY WAY

Space is Vast

If you want to go somewhere you have several questions you need to ask yourself- how far away are you traveling, followed by what do you want to do when you arrive? On earth the distance we travel frequently determines the best mode of transport. If you need to go far, say 5000 kilometers, and want to get there in a reasonable length of time you would likely go by airplane. If you are going only 500 kilometers then you would like to go by car, or bus or train. If you are going 500 meters you will likely walk. However, in addition to distance, what you want to do at your destination may determine your transportation. A vacation may require a far different mode of travel than if you are moving somewhere for a new job.

The nature of what lies between “here” and “there” also can determine the mode of travel. For instance, if there are no roads, you may have to fly by plane or helicopter. No airports- then perhaps you go by train or car.

When we travel in space, we need a spaceship. The type of spaceship, its size, its speed, its capabilities, need to be tailored for the distance and the environment to be traveled. The places we choose to go can range from relatively close to distances so vast that they are literally incomprehensible. Furthermore, while space does not have weather as on earth, conditions do change. If we are traveling near the sun, the heat and radiation issues will be very different than a spacecraft that is only traveling in deep space. Landing on an asteroid will require different capabilities than if we were to land on another planet or moon.

One thing that remains consistent when dealing with space is that even the objects that are closest to us, things like the moon or Mars are, when compared to our earthly travels, extremely distant. In everyday life, it is difficult to appreciate how vast the distances in space are- the numbers can quickly become so huge as to be meaningless. To get anywhere in space requires tremendous speed, or a lot of time- and frequently both.

How big is space? Over the last few hundred years, as the true size of space has dawned on the astronomers that study it, there have been many attempts through analogies and comparisons to try and capture its scale. The reality is that even these examples sometimes just leave one with the impression of “wow, space is really big”. Try as we might the human mind can think of the scale in abstract but can’t really grasp the scale in practical terms. This is shown nightly on science fiction TV shows or in movies where people can conquer the distance in at most a few days or weeks of travel and get to the next interesting world. The reality is that this sort of travel will likely never happen and throughout this book this will become clear.

The earth is about 12,742 km across. The Moon is our closest neighbor and is 384,400 kilometers away or the equivalent of 30 earth diameters. The planets are even further away- the numbers quickly become very large. A car traveling at 100 kilometers per hour (about 62 mph) would take 3844 hours to get to the moon- about 160 days of non-stop driving. The sun averages about 150,000,000 kilometers away or the equivalent of 12,000 earth diameters. To drive from the earth to the sun at 100 kph would take 1.5 million hours- or 176 years of driving.

And the distances just get bigger as we go farther out into the solar system. Neptune would be the equivalent of 360,000 earth diameters from the sun- over 4 billion kilometers. A non-stop drive to Neptune would take about 4500 years.

Because Kilometers are so small and the distance to astronomical objects so large, astronomers frequently use other units of measure to try and make the numbers more meaningful. One common unit is the Astronomical Unit or as it is frequently referred to, an AU. An AU is the distance from the earth to the sun or, as mentioned, about 150,000,000 kilometers. Hence the earth is one AU from the sun and Neptune would be about 30 AU- or 30 times further from the sun than we are. The AU is convenient to use when referencing travel within the solar system- it uses a distance that the average person understands (the distance to the sun) and it is large enough that it does not generate huge meaningless numbers.

The nearest star is 268,000 AU away so even this unit is too small when describing missions to the stars. For really long distances, scientists and engineers frequently use the speed of light and how far it travels in a certain amount of time as a unit of distance. Light travels at the considerable speed of 300,000 kilometers per second.

If you have a powerful enough flashlight and pointed it at the moon and turned it on, it would take about $1\frac{1}{3}$ second for the photons from that flashlight to travel from the earth to the moon where (if someone had VERY sensitive eyes) they would see the flash of light. One way of stating this is that the moon is $1\frac{1}{3}$ light seconds away from the earth.

Light travels one AU in about 8 minutes and 20 seconds. To get to Neptune light would take a little more than four hours. In one year, light would travel 9,460,800,000,000 kilometers (that is over 9 trillion kilometers)- or a light year. A light year is about 63,241 AU.

Using various measures, we can identify the following distances (from the sun) to other planets in our solar system:

Object	Million Kilometers from the center of the sun	AU (from Sun)	Light minutes
Mercury	57.9	.3870987	3.2
Venus	108.2	.723332	6
Earth	150.0	1	8
Mars	227.94	1.523	12.7
Jupiter	778.57	5.2011	43
Saturn	1,433.53	9.5826	80
Uranus	2,875.04	19.2185	160
Neptune	4,500.000	30.07	250
Kuiper Belt	4500-7500	30-50	250-400 (4.1- 6.67 hrs.)
Oort Cloud	190,000- 2,000,000	2000-20,000	16,000-160,000 (11- 111 days)
1 Light Year	9.46×10^{12} km	63,200	525,000
Nearest Stars	4.1×10^{13}	265,000 +	2,300,000

TABLE 1-1 SOLAR SYSTEM DISTANCES FROM THE SUN

Albert Einstein's general theory of relatively established that it if an object has mass, it is impossible to reach the speed of light and that, indeed, as one gets closer and closer to light speed its mass grows and it takes more and more energy to accelerate until, at the speed of light the energy requirements become infinite. Albert Einstein and his general theory of relativity establishes the mathematical foundation as to why this is true and nearly a century of experiments have proven the theory incredibly accurate in its predictions of both gravity and how object behave as they approach lightspeed. Even

though the details of why this is true are outside the scope of this book the effects are important and can be summarized by a few bullets.

To a “stationary observer”

- If you observed a spaceship traveling near the speed of light activity on the spaceship would appear to slow down to the stationary observer. One result of this is that to the stationary observer, that last molecule of fuel that would bring you to light speed will never get burned or consumed. This is referred to as the time dilation effect.
- As you approach the speed of light your apparent mass approaches infinity

To the person approaching the speed of light:

- Time on board the spaceship would not appear to change.
- The corollary to the observations of the stationary observer is that the passenger traveling at near the speed of light will see the outside universe appear to speed up. Indeed, if he were really close to the speed of light (say 99.99999999%) it would appear that the universe would age billions of years in a few seconds. In the now famous short story, which he later expanded into a book, *Tau Zero*, Pol Anderson explored this theme with a “runaway” starship whose engines could not be shut down and approaching closer and closer to the speed of light. The end result is that the crewmembers live to witness the death and rebirth of the universe.
- Other interesting effects would occur as you approach the speed of light— for one you actually would not be able to see much of this universe because your view of the universe would contract to a smaller and smaller point directly in front of you. You would be traveling so fast that the light from behind you would barely keep pace with you, the result that the light would gradually dim and become red shifted, eventually into the infrared and then radio waves. In front of you would be heading into the starlight so fast that the light would get brighter and bluer- eventually drifting into x-rays and then gamma rays.

Because of the time dilation effect and the increase in apparent mass, it is an absolute rule that nothing with mass can go at the speed of light. This does not apply to massless items like photons which do travel at light speed. From a photon’s perspective, time does not exist. Furthermore, the rules do not prohibit things from going faster than the speed of light though how you would jump from just below light speed to above light speed without going past the speed of light is beyond our understanding and will likely remain so.

There are other aspects of the finite speed of light that we must consider when building a spaceship. When we use a radio (or laser) transmitter the speed of light limits how quickly a signal can get from the transmitter to receiver. This is the reason that robot probes that go to the planets have many of their functions automated. When you are exploring Mars with a robotic rover, depending on where the Earth and Mars are relative in their orbits, signals can take anywhere from 5 to 24 minutes to travel between the two planets. Needless to say, it would be extremely difficult to remotely operate a vehicle with an 5-to-24-minute time lag.

Because it is hard to grasp its enormity of space, it is easy to under appreciate the difficulty of traveling to the stars. Our sun is about 1,391,400 km in diameter. Light takes about 4.64 sec to travel across this diameter. The nearest star would be about 4.3 LY away. If we reduced the scale of the universe such

that our sun was the size of a marble (of about 13mm), the earth would be a small grain of sand orbiting a little over one and a half meters away. The moon would be orbiting our grain sized earth a little less than 4mm away. The most distant planet, Neptune, would orbit about 41m away from our marble sized sun.

Using this scale, the nearest star to our sun would be another marble 370 kilometers away!!! At this scale even the largest starship we could build would be smaller than the smallest bacteria. It would need to not only travel 370 kilometers but have to come within a meter or two of this second marble. Keep in mind that this voyage of 370 kilometers may take many, many centuries and all during this time the two marbles are moving in relationship to each other as they orbit independently around our galaxy's center. To carry this image even further, the center of our galaxy would be almost 6000 times further- or over 2,270,000 kilometers away from our marble sized sun!

This is a typical distance between stars in our galaxy and should illustrate why collisions between drifting stars almost never occur. The journey we plan to make is indeed daunting!

To go to the stars, ideally you would like to go as close to the speed of light as possible- 300,000kps. On earth, the only manmade items that go nearly this fast are individual atomic particles in particle accelerators. In the everyday world larger objects travel much slower. Here are some typical speeds:

Commercial jet= .25 kps

Fighter Jet= .5-.7 kps

SR-71 Spy Plane= 1kps

Bullet (gun to rifle) = .75-1.5 kps

Missile= 6kps; To travel 10 light years at 6kps it would take 500,000 years!

The Voyager 1 spacecraft is the fastest spacecraft man has ever sent out from the Solar System. It's leaving at a velocity of around 17kps. At this speed a voyage out to 10 light years would last about 150,000 years- much faster than our 6kps spacecraft but likely far too long for the missions we will be considering.

Space is Empty

Just as the size of space is difficult to grasp, other aspects of space are also intimidating.

For one thing, it is tremendously empty. As we discussed stars are so far apart as to be almost indescribably distant but the fact that we can see stars across these vast distances means that there is not much between us and the stars. If you think about it, a telescope can see to the furthest galaxies in the universe- whose light has taken over 13 billion years to get this far¹. This means that the space

¹ These distant galaxies are actually far more distant than 13 billion light years. Light has taken 13 billion years to get to the earth from the most distant parts of the universe but since the universe is expanding, the actual galaxies have since moved much further away.

between that galaxy and the telescope is empty and transparent- filled with the merest wisps of gas and dust.

On earth, at sea level there are about 2.5×10^{19} molecules per cm^3 . In our solar system, in what is called interplanetary space, this is reduced to about 11 particles per cm^3 . Outside of the sun's domain, in the space between the stars known as interstellar space, the number of molecules drops down even further to 1 particle per cm^3 . Even more impressive, in the space between the galaxies (so called intergalactic space) the density drops even lower- to only 10^{-6} particles per cm^3 .

If we use the density of interstellar space of 1 particle per cm^3 , then you could take a cm^3 of earth's sea level atmosphere and stretch it $2.5 \times 10^{19} \text{ cm}^3$ to reduce it to the same density as interstellar space. $2.5 \times 10^{19} \text{ cm}$ is a long distance- 2.5×10^{14} kilometers! Another way of looking at this is you could stretch the one cm^3 of earth's atmosphere out to about 26.4 light years to get to the density of interstellar space.

The vacuum in Intergalactic space is even more extreme- one cm^3 of earth's sea level atmosphere could be stretched out to 26,400,000 light years to contain the same number of molecules.

Space is Massive and Resource Rich

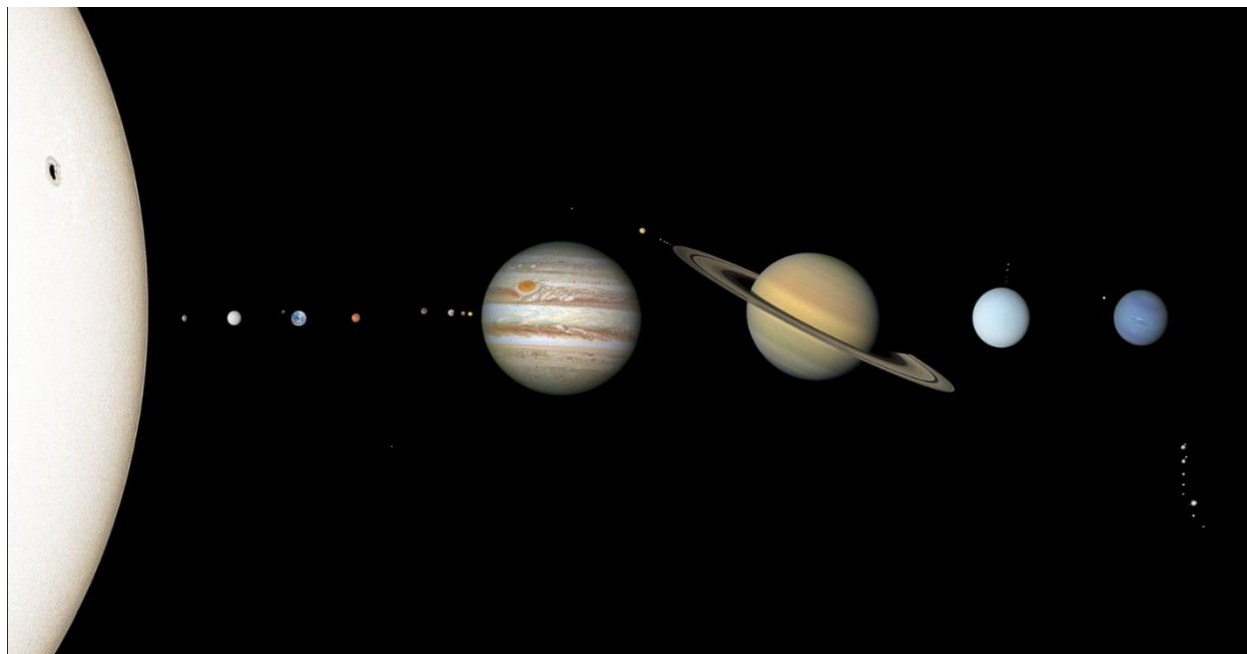


FIGURE 1-2 THE PLANETS TO RELATIVE SIZE SCALE IN ORDER: SUN, MERCURY, VENUS, EARTH, MARS, JUPITER, SATURN, URANUS, NEPTUNE WITH THE LARGEST MOONS AND MINOR PLANETS

The lack of matter across interplanetary, interstellar, and intergalactic space may imply that there is not much material in space. This may be true if you are looking at a particular volume between the stars but on large scales this is not the case. For starters, as we have just seen, even though a cubic meter of space is mostly empty, the sheer volume of space is tremendous. Think of our example where we

reduced the size of the sun to a marble and the nearest other star was 370 km away. Even if the density of matter around the sun was very low, the volume of space with each marble being on average over 370 km away could still contain a lot of matter. Furthermore, most material is consolidated into very compact volumes like stars and planets. About 91% of normal matter (also called Baryonic matter) is tied up in the stars and planets. Only about 9% is dust and gas. Astrophysicists believe that there are other forms of matter and energy in space- including Dark Matter and Dark Energy, but these are not relevant to our current discussions since they are invisible and interact barely at all with normal everyday matter.

From our perspective here on earth, the quantity of raw materials in the universe is almost incomprehensible. Compared to everyday human experience, the earth is tremendously massive, and the sun is vastly larger still. Our Sun is 333,000 times more massive than the earth; Jupiter is 318 times and Saturn 95 times more massive. Appendix E gives some planetary specifications.

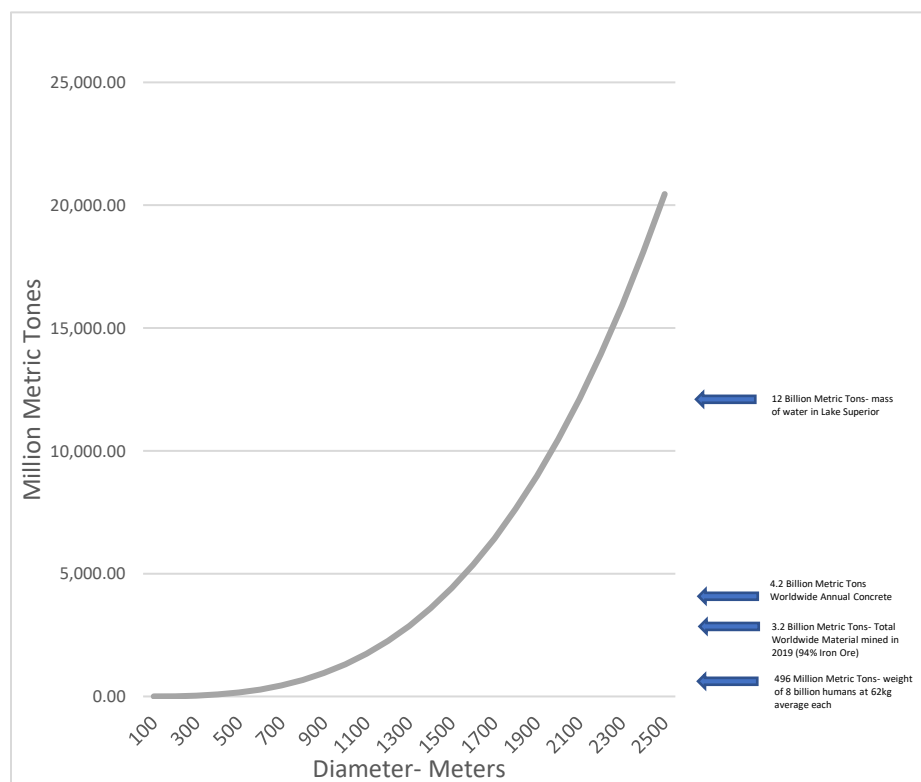


FIGURE 1-3 DIAMETER OF ASTEROID VS MASS (ASSUMING 2.5SG) IN HUMAN TERMS (BHUTADA, 2021)

(SG) of 1.0), but some asteroids, especially M type metal asteroids, have an SG closer to 4. If we choose a value in-between of a SG of 2.5 we get Figure 1-3.

What this chart shows is that even small asteroids only a kilometer or two in diameter have a tremendous mass on human terms. It is estimated that there are 200,000 asteroids 3km and larger in the solar system (Bottke, et al., 2005).

The sun converts about 600,000,000 tons of hydrogen into about 596,000,000 tons of helium and 4,000,000 tons of energy every second (per Einstein's famous equation $E=mc^2$). At this rate, the sun

On the earth, we frequently are concerned with running out of natural resources but when we look at it from a macro perspective, the raw material supply on both the earth and in space are virtually inexhaustible.

An understanding of how much mass is in our solar system can be gained by looking at the amount of material tied up in small asteroids or comets. These small bodies vary tremendously in density depending on many factors. Comets in particular are usually only a little denser than water (Specific Gravity

consumes the equivalent mass of the earth in about 315,500 years. At this profligate rate of consumption, it is estimated that the sun would burn for a total of 10 billion years before it runs out of fuel. The sun, at an estimated age of 4.5 billion years, is middle age and about halfway through the hydrogen burning portion of its life.

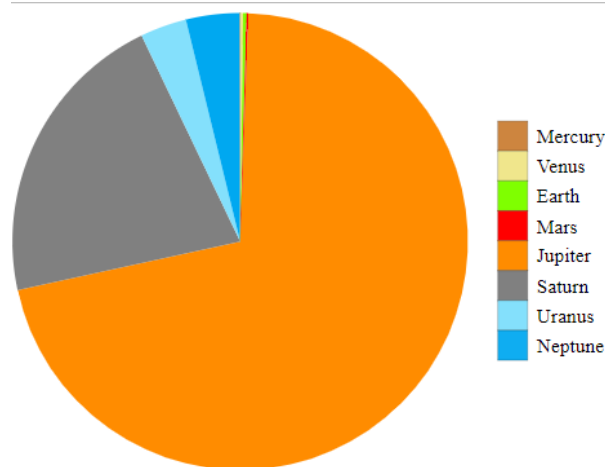


FIGURE 1-4 RELATIVE MASS OF THE PLANETS

Planets can lose their atmosphere over long periods of time. With small planets having weak gravitational fields, the mass loss situation can be severe especially if they are close to the sun. The Earth loses up to several hundred tons of atmosphere (mostly oxygen) per day (Hatfield, 2018). Mars, in particular, is believed to have lost most of its atmosphere earlier in its history and still loses at a much lower rate of 1kg every 10 seconds (Northon, 2015) which equates to a little more than 3000mt per year. All these numbers are an insignificant portion of the planets mass since, as indicated by the aptly named “rocky planets” (as opposed to the four “gas giants”, Jupiter, Saturn, Uranus, and Neptune), almost all of the rocky

planet’s mass is rock.

When talking about almost any aspect of raw materials in the solar system the numbers become huge. How does this translate into more understandable numbers that humans could deal with? Figure 1-3 gives an idea. As another example it is estimated that the earth’s population generates 2.01 billion tons of trash each year (or 2.01×10^{12} kg) (World Bank, 2016). This makes the Saturn V mass of about 3,000 mt seem trivial. But compared to the mass of various objects in the solar system this, in turn would be insignificant. Using the graph in Figure 1-3 we can see that this equates to an asteroid slightly smaller than 1.2 kilometers across. The mass of the largest asteroid, Ceres, which is only $1/78^{\text{th}}$ the mass of the moon would dwarf these numbers. Ceres weighs about 9.38×10^{20} kg. It would take about 467 million years for the world to generate a ball of trash about the size of Ceres²- or a period of time that would extend back to far before the dinosaurs.

To finalize the point about the mass of things, the earth itself weighs about 5.97×10^{21} metric tons or about 6250 times more than Ceres.

The original makeup of the universe was hydrogen and small amounts of helium along with traces of Lithium. Over time this hydrogen and helium has been sequestered into stars and other objects (primarily planets) in a galaxy. As the universe ages it becomes enriched in “metals” as stars convert the original hydrogen/helium into heavier elements. The source of all the remaining items in the periodic table varies. In some cases, the largest stars liberate some material during supernova

² Note that this trash is only trash in the narrow sense- as material that is not needed and being disposed of. Trash is made up of many materials that can be recycled or, if not, broken down over time by biological processes and/or heat. This is because, as has often been stated, matter and energy cannot be destroyed just changed from one form to another. None of the trash generated has ever left the earth- it just changes form.

explosions, but other materials are liberated from dying low mass stars or even exploding white dwarfs and merging neutron stars. The table below shows the source of all the elements in the Universe.

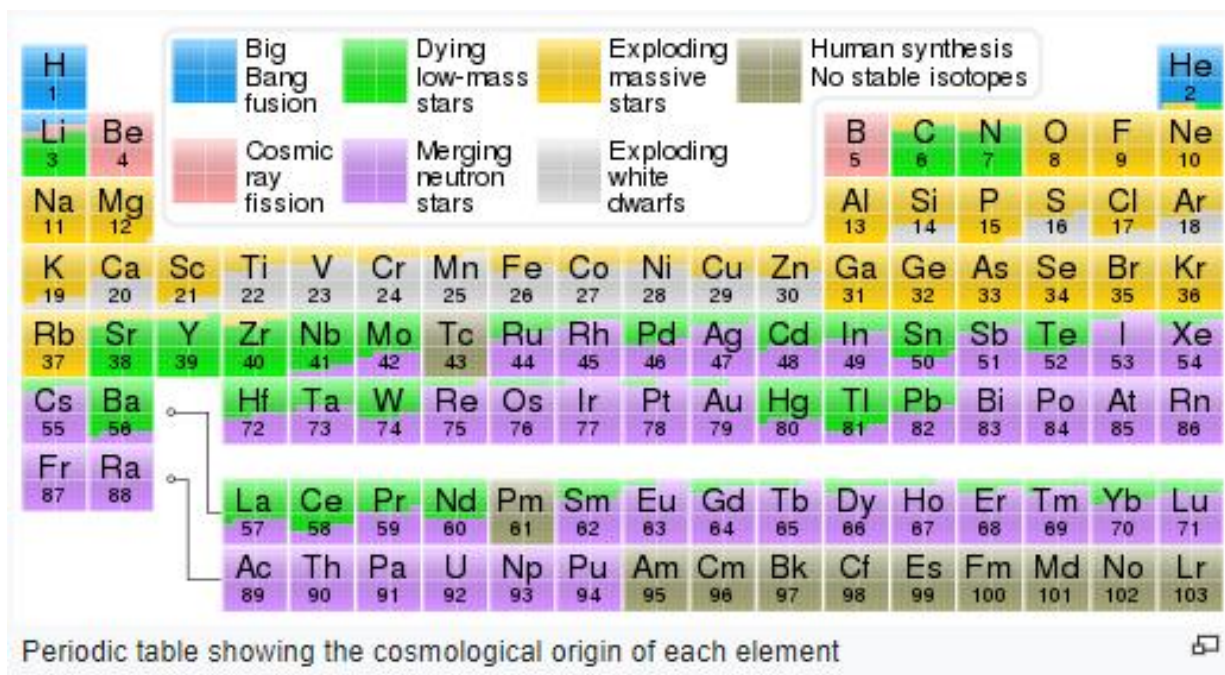


FIGURE 1-5 THE TABLE OF ELEMENTS WITH THEIR ORIGIN (CMGLEE, 2017)

The Nearest Stars- Where would we go?

In our Galaxy, the Milky Way, it is estimated that there are at least 100 billion stars. The nearest star to our sun is just over 4.3 LY away. The sun is about 28,000 light years from the galactic center and stars on the opposite end of our galaxy are about 70,000 LY away. It is obvious that the nearer the star is to us, the easier and quicker it will be to travel there. However, many stars are poor targets, and this includes many of the stars nearest the earth. Many articles and books have been written about what makes a star habitable- but they usually focus on finding and inhabiting relatively earthlike planets. This may be too restrictive as virtually all stars are habitable if we have large artificial constructs either on planets or moons or on large space stations. Nevertheless, we do need to develop minimal requirements for a crewed mission.

First let us consider some facts about stars and our Milky Way. Almost all stars in our galaxy orbit in the same direction around the galaxy's core. The core of the galaxy is a relatively dense region of older stars formed early in our galaxy's history. At the center of our galaxy is believed to be a large black hole of about 4 million solar masses. Our galaxy is called a barred spiral- looking somewhat like a pinwheel when viewed from above or below. From the side it appears like a flattened pan. This shape is a typical shape for many galaxies except that our galaxy is somewhat larger than average. It is approximately 100,000 light years from end to end, but only a few thousand light years thick at the center and gradually dwindling off to a few hundred light years at the outer ends of the arms. The central bulge at the core is densely packed with old stars and is about 10,000 light years wide. As mentioned, the total galaxy is estimated to contain about 100 billion stars, but there are some astronomers that believe this undercounts very small and dim (and therefore hard to see) stars and that the galaxy may contain up to 400 billion stars. Our sun is a solitary star whereas most stars in the galaxy belong to binary, triple, or even larger star systems. As opposed to frequent statements in the popular media, our sun is actually brighter than 95% of the stars in our galaxy. With at least 100,000 billion stars in our galaxy, this means that about 5 billion would be larger than our sun. Larger stars burn through their nuclear fuel much faster than dimmer stars so that a very large star (several times the mass of our sun) might burn through all its fuel in a few million years and explode in a supernova. Conversely, small, low mass stars burn very slowly and might last trillions of years. When you look at the night sky most of the stars that you see are far brighter than the sun, so this gives the impression that there are a lot of very bright stars. In reality there are many more dim stars that you just can't see.

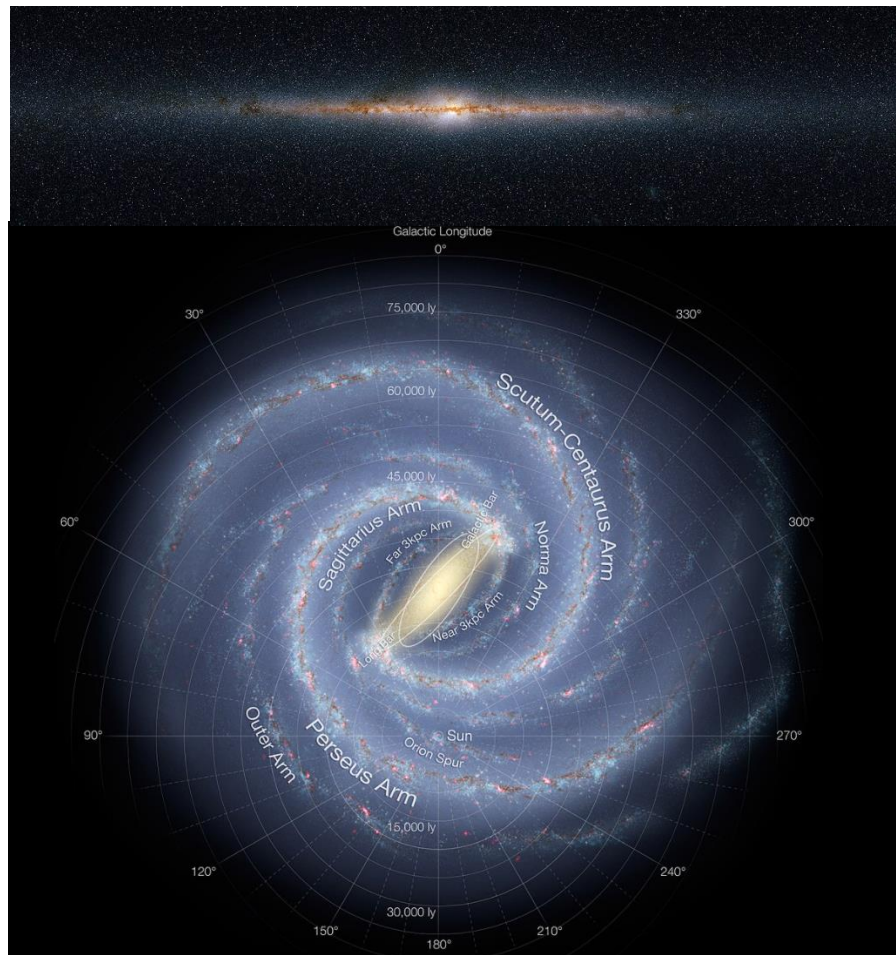


FIGURE 1-6 OUR GALAXY (NASA/JPL- CALTECH/R. HURT, 2017)

How do we calculate distance to the stars? For near stars, we use the parallax method. This is a direct measurement and for nearby stars is very accurate. If you take a photograph of a nearby star, and then again six months later, it will seem to have shifted (slightly) compared to more distant stars. This is because, during the six-month period, the earth has moved around the sun 180deg and would be 2au shifted from the first photograph to the second. Using simple geometry by figuring the parallax angle you can calculate the stars distance. Of course, just because the math is straightforward, actually calculating the distance to a star is never simple- the angles of even the nearest stars are tremendously small.

The equation for calculating the distance is as follows:

EQUATION 1-1 $\tan(p) = \frac{1au}{d}$

EQUATION 1-2 $d = \frac{1au}{\tan(p)}$

Parallax measurements is the source of the unit of parsec. A parsec, by definition, is the distance that an object where the angle $p =$ subtends 1" (1/3600 of a degree- or 1 arc second) (see Figure 1-7). To calculate the parsec:

Using Equation 1-1 and rearranging the terms:

EQUATION 1-3 $d = \frac{1au}{\tan(1'')} = 206,265au$

Using the value 1au= 149,600,000 km, a parsec represents 3.2616 Ly

Just measuring the parallax distance to the stars is an oversimplification of what really happens. It must be kept in

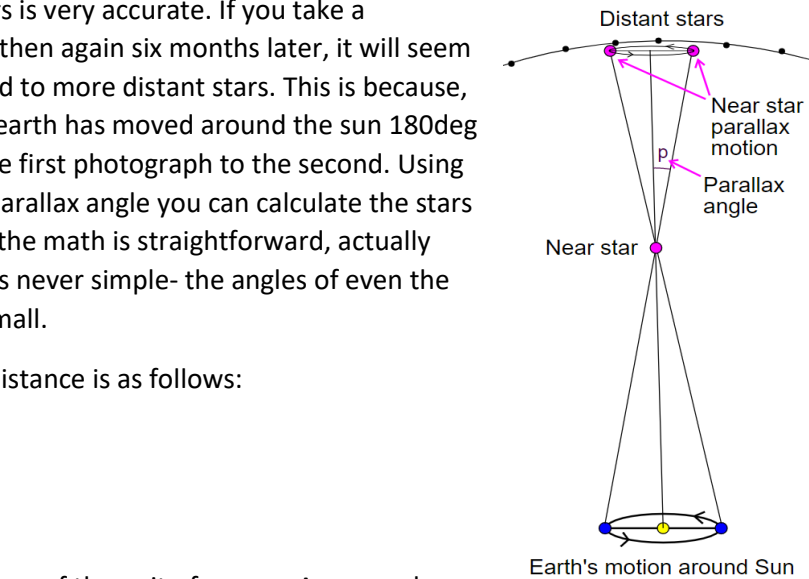


FIGURE 1-7 PARALLAX



FIGURE 1-8 GRAPHICAL REPRESENTATION OF A PARSEC

mind that during the 6-month period that the earth has traveled around our sun, the sun has also moved relative to other stars (Figure 1-9). Because of this motion of the sun the earth has followed a corkscrew pattern when seen from another star. The motion of the sun through space therefore creates its own parallax- referred to as secular parallax. The secular parallax is frequently larger than the earth's parallax around the sun and this complicates the determination of distance. Further complicating matters is that the sun has different relative velocities to other stars so its secular parallax will vary for every nearby star. Finally, when you take a parallax measurement all stars would shift making it difficult to tell what the actual absolute distance is. You must ensure that the star you are measuring is much closer than the background stars so as to get an accurate measurement of the shift. All these factors make it challenging to extract the true distance to stars. Nonetheless, with modern instruments and powerful computers to analyze, the distance to stars out to a few hundred parsecs can be accurately determined. In particular, the ongoing European Space Agency (ESA) Gaia Spacecraft missions' goal is to

accurately capture the parallax of about 1 billion stars in the Milky Way (1% of the Galaxy's population) over its planned 10+ year mission. (ESA, 2019).

What kind of stars would we want to visit or colonize? To some extent this is determined by what we want to do. If we just want to send a probe to a star, we are likely to be happy sending our probe out to almost any star- as long as there are some interesting things to explore. If we want to send a colony then there are two alternatives that have been looked at for long term habitation- building large artificial space stations at the new star, or colonizing any earth like worlds that may be there. If our goal is building large colony space stations, then we just need to visit a solar system that has raw materials available to build our colony. However, if we would like to find a star with an earthlike planet (as in most science fiction) we may have to go very far- to date no earth-like worlds have been definitively identified around any of the nearby stars. This is partly because it is so difficult to find a small planet around a brilliant and distant star.

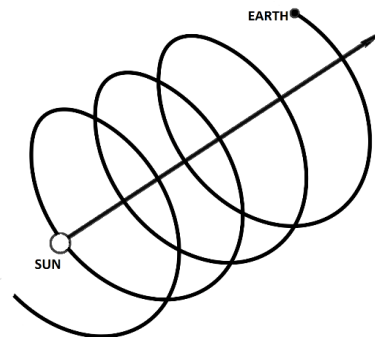


FIGURE 1-9 MOTION OF SUN/EARTH THROUGH SPACE

What does it mean to be an “earthlike planet”? Some criteria that we may consider are:

1. Gravity is similar to the earth.
2. Material makeup and density are like earth. If a planet is as massive as earth but made of all gas or water, it will not be habitable- at least by us.
3. Solar heating like ours (orbital distance will vary tremendously depending on the intrinsic brightness of the star).
4. A stable orbit. A planet in a large elliptical orbit will have substantial changes in solar radiation throughout its year that will cause severe climate changes.
5. Atmosphere like earth. This may be very rare as the earth's natural atmosphere would contain no oxygen. Oxygen is so reactive that it will readily combine with anything- Hydrogen to make water, Carbon to make CO and Iron to make rust. Free oxygen only exists because we have organisms on earth that constantly refresh our supply.
6. Related to item #2, a rocky planet with similar surface composition to earth- to include water to give us oceans. This is a hard one. The earth has plenty of water to give us deep oceans, but not too much to drown the continents. We can see throughout the Solar System examples where the whole surface, down many hundreds of kilometers, is ice. Large moons like Europa, Ganymede, Callisto, Titan are totally encased in ice with the rocky surface hundreds of kilometers below the surface. These moons, along with many others in our solar system, have far more water as a percentage of mass than the earth. If these moons were closer to the sun, they would be covered by oceans hundreds of kilometers thick. Conversely, we have some dry worlds (the Moon, Mercury, Venus, Io) that have little or no water. Venus likely had lots of water once but experienced a runaway greenhouse effect that boiled it off. Eventually its water molecules rose high into its atmosphere where it was split by ultraviolet radiation from the sun where the hydrogen floated away (Venus' gravity is insufficient to hold onto hydrogen) and the oxygen stayed behind to combine with Carbon to form CO₂. Gas giants are usually not considered for colonization as they usually are very massive with deep gravity wells, and the

needed resources (including a place to land) are non-existent. One thing to consider is that even though the gas giant would not likely be of interest to colonists, large gas giants may contain large moons that may be suitable for colonizing. I would also include systems that have minor planets (i.e. asteroids, Kuiper belt or Oort Cloud) as qualifying. This existence of these in other star systems is frequently unknown due the small size of these objects making them difficult to spot, but it is anticipated that if the evolution of solar systems are pretty similar, that most stars would have these sorts of objects orbiting them. While there are star surveys that indicate planets are around a sizeable portion of stars (recent estimates say about 70%) to confirm a planet around one of the nearer stars has been difficult. Statistically NASA estimates that about one of six stars have an earth sized planet close into their star. The target planet(s) should be at a reasonable distance from the parent star- not too close so that accessing the raw materials would be impossible due to the intense heat and radiation, nor too far where solar power (which would supplement or be the primary power source for very large habitats) would be unworkable. This does not mean to say that the planets need be in the stars' habitable zone- our range would be much larger.

7. Planetary Magnetic Field- an active magnetic field may help protect the planet's atmosphere from being stripped away over time by the solar wind. In our solar system, when considering only the rocky planets, moons, and asteroids, only the earth has a strong magnetic field.
8. Required to be tectonically or volcanically active. The planet can't be geologically dead. Over billions of years if a planet is warm enough to support liquid water, the water will eventually percolate into the ground. If the planet is geologically dead, there is no way to recycle this water back up to the surface. It is likely that Mars has substantial reservoirs of water under the surface, but volcanic activity is so low that it is no longer brought to the surface. Furthermore, it appears that a geologically active planet is necessary to generate a substantial magnetic field (Item #7)

Despite all these criteria most astronomers are confident there will be many earth like planets in our galaxy. Considering that there are 100 billion stars in our galaxy, even if only one in ten thousand stars has an earthlike planet there would still be ten million earthlike worlds. The only discouraging part is that even with ten million earth like worlds, the galaxy is so large that the nearest earthlike planet may easily be five hundred light years away.

As of 2022 NASA states that about 5000 planets have been identified (NASA, 2022) in our Galaxy. From a habitability standpoint, little is known about these planets. The only items that we know reasonably well are the orbital periods around their stars which gives us information on how far they orbit which, in turn, gives us an indication of the possible temperature of the planet. Less is known about the planet's mass (though approximations can be made) and even less as to whether the planets have an atmosphere. It will take further telescope improvements to determine the habitability of many of these worlds (more about this in Chapter 16).

We know considerably more about the stars themselves. For a manned exploration or colonization of the nearest stars, let us impose loose constraints on them that meet the following minimal conditions:

1. The star must be stable. This is a relative concept but would eliminate the most extreme stars- those that have frequent solar flares that can emit a lot of ultraviolet radiation. We can also eliminate stars that are very old and getting close to becoming a nova or supernova.

2. Star must be large enough to provide adequate energy for Solar Power for the colonists and to warm up a few planets. Historically it was felt that only stars that were like the Sun (Class G), or K type stars, (see Table 1-2) qualified. G type stars make up only about 7% of the solar population. K and G type stars have surface temperatures of 4000K to 6000K. More recently some have speculated that smaller stars (M type) may still be able to support life- though solar panel efficiency for colonists may be a challenge- M type stars emit a much higher percentage of their radiation as infrared and solar panels usually do not work well with primarily infrared. Note also that due to the low heat and light outputs of M type stars, any habitable planets would have to be very close to the star- perhaps only 5-10 million kilometers with orbital periods of only a few weeks. In general A, B, and O stars have not been considered prime candidates for habitable worlds. O and B stars may only last a few million years and even A type stars do not live long enough to have mature, settled down solar systems. A convenient rule for calculating how long a star lasts is:

Class	Temperature	Sample star
O	33,000 K or more	Zeta Ophiuchi
B	10,500–30,000 K	Rigel
A	7,500–10,000 K	Altair
F	6,000–7,200 K	Procyon A
G	5,500–6,000 K	Sun
K	4,000–5,250 K	Epsilon Indi
M	2,600–3,850 K	Proxima Centauri

TABLE 1-2 TYPES OF STARS

EQUATION 1-4 $\frac{t_{MS}}{t_{\odot}} = \left(\frac{M}{M_{\odot}}\right)^{-2.5}$

Where $t_{\odot}$ = lifespan of sun (10billion years or 10^{10} years)

M = mass of star

$M_{\odot}$ = Solar Mass

3. Must have a planet/planets or minor planets (asteroids like bodies) orbiting the star with the criteria previously indicated. At least one of the planets must be rocky.
4. Binary and multi-star systems may be problematic. It is estimated that a third of all star systems are either binary or multiple. Even though most star systems are single, the fact that 1/3 of star systems are binary or multiple means that about 85% of the stars are actually part of a binary or multi-star system. It should also be noted that binary or multiple stars are much more prevalent when looking at more massive stars- 80% of O and B size stars are part of binary or multiple star systems. For red dwarfs (believed to make up 85% of all stars) only about 25% are binary or multiple star systems (Lada, 2006).
 - a. If a binary system and the two stars orbit very far apart (hundreds of AUs) then either star may still be able to have planets orbiting in stable orbits. If the stars approach each other close (say a few dozen AU) then over time these stars will either prevent planets from forming or disrupt the planets orbits and eventually either fling the planet out of the system or cause the planet to crash into one of the stars.
5. Access to volatiles. Besides a rocky planet or minor planets, there must be a source of volatiles- either planets, moons, or comet like bodies that will be able to provide items like nitrogen, water etc.

6. The Target star needs to be middle aged. Stars whose planets are still developing, are very dangerous- filled with dust and rock that would make it impossible for a spaceship to approach and make any planets dangerous to colonize. In addition, young solar systems, with large numbers of asteroids and comets may have significant instabilities to include migration of planets orbits. It may take several hundred million years for the solar system to become stable.

To date, none of the stars near the earth have been confirmed to meet all these criteria. Items 1, 2, 4, 5 and to some extent 6 are easily determined from earth and, for now, will be the basis for us selecting target stars. The most important item is number three and this is usually unknown because identifying the details of a planet around a star is tremendously difficult. There are four primary techniques that account for a vast majority of all extrasolar planets identified:

1. Direct visual observation. The challenge with this is that stars usually outshine even a large a planet by many millions of times. The glare of the star makes detecting planets orbiting the star almost impossible.
2. Doppler shift. Another technique is trying to detect a planet by the gravitational effects they have on their parent star. As with detecting planets with light, detecting a planet by its gravitational effect is also difficult- a planets mass may be only a few hundred thousandths of the stars, but compared to its reflective light technique is method #1, the gravitational effect is much larger and easier to determine. The Star and planet will orbit around a common center of mass (usually deep within the star) but nevertheless the star will wobble a bit as the planet swings around. When the star swings towards the earth it will have a slight shift toward the blue end of the spectrum. When the planet swings around to the opposite side of its orbit (depending on how close to the star the orbit can be anywhere from days to years) the stars will shift slightly away from the earth and the spectrum will be shifted toward the red end of the spectrum. Like many of the planet detecting techniques, this method will pick up a large planet easier than a small one.
3. Gravitational Microlensing- where the planet passes in front of a more distant star. Gravity can bend light and serve almost like a lens- temporarily causing the distant star to brighten. This is a relatively infrequent occurrence and likely to be only a single event and not repeatable.
4. Transit. If the planet's orbital plain around its parent star is lined up to the earth, then every time the planet crosses between its parent star and the earth we will see a slight dip in the light emitted by the star. This technique is in many ways the most definitive and has been responsible for detecting a vast majority of the known extra-solar system planets. The problem with this is that it is random as to the orientation of the planets orbital plain so that only about 1% of stars planetary system are correctly aligned with the earth. The Kepler observatory used this method. Even though it only works for the approximate 1% of the stars observed, it is relatively easy to monitor a large number of stars. Kepler monitored about half a million stars.

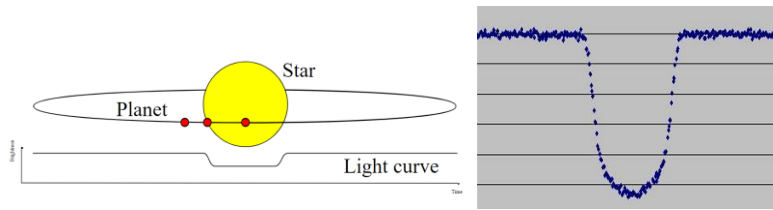


FIGURE 1-10 TRANSIT OF STARS

Within 20 LY of earth there are over 100 stars. Meeting the criteria of a habitable zone is challenging. In appendix B, I have listed the nearest out to 16 light years, with a color grade that I assigned for potential desirability. I say potential because for many of these stars it is still uncertain as to whether or not they actually contain planets. One unfortunate conclusion that you can take from the appendix is that except for a couple of exceptions, most of the candidate stars are more than 10LY away.

Habitable Zones

There are many different models of what a habitable zone is but in general it is the distance range from the parent star where water is liquid. The only thing we know for sure is that the earth is in a habitable zone because we are here! There are so many variables that can determine a habitable zone which complicates the situation. For instance, Mars is not very habitable in its current configuration, but if Mars were larger and with a thicker greenhouse atmosphere it may have been able to support liquid water and be in the habitable zone. It is believed that Mars did have liquid water and a much thicker atmosphere in its first billion years of existence. Similarly, Venus may have been in the habitable zone in its first billion years when the sun was about 25% less bright.

Habitable zones are primarily driven by heat. Too much and the planet becomes an inferno. Too little and surface water or even its atmosphere, will be frozen. Unfortunately, determining the habitable zone based on just the distance from and magnitude of the star does not give the whole picture. A planet's atmosphere- its thickness and composition- can affect the width of the habitable zone. For instance, Venus is hotter than Mercury because of a very thick atmosphere of CO₂, a greenhouse gas, even though Venus receives only about ¼ of the radiation that Mercury gets. Similarly, the Earth is on average, a comfortable 15°C, but if the earth had no atmosphere, it would be about 33°C cooler- or about -18°C and likely frozen solid from pole to pole.

Furthermore, the size of the star impacts the habitable zone in even more ways. A small star, besides being intrinsically dimmer, also radiates in a cooler (redder) part of the spectrum. Table 1-2 shows that an M type star has a surface temperature between 2600K and 3850K- about half that of the sun. A planet orbiting a small red star will therefore have to be much closer to the star to stay above the freezing point of water. The picture is even more complicated as small stars are often flare stars, that is

they have solar flares that increase their solar winds that can strip away the atmosphere of a close or small planet that does not have a strong magnetic field to protect it.

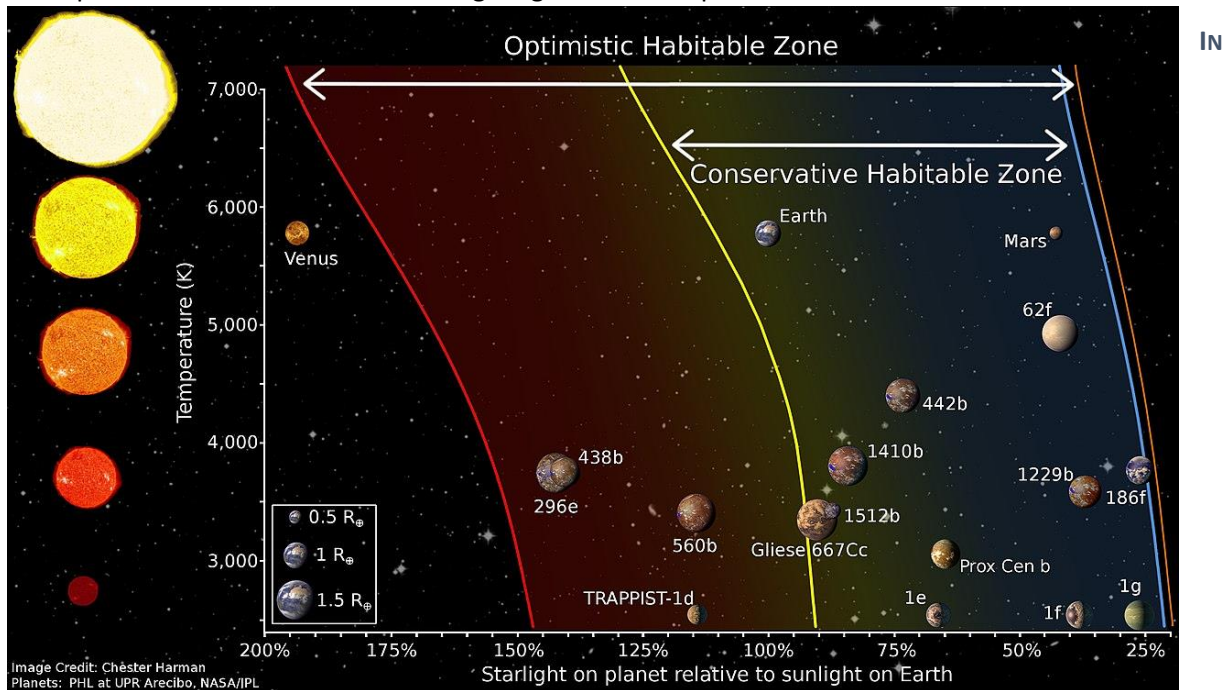


FIGURE 1-11 (HARMAN) HABITABLE ZONE, STAR TEMPERATURE AND RELATIVE STARLIGHT

In addition to the amount of heat a planet gets from its parent star, planets can't orbit too close, or risk being tidally locked which means that the same face is always pointed to the star. Almost all moons in our Solar System are tidally locked with their parent planet. None of the actual planets are tidally locked with the sun but Mercury likely could have been if it was not in such an eccentric orbit which locked it in a 3:2 spin-orbit resonance whereby it spins around on its axis three times for every two orbits.

Regardless, a small body closely orbiting a much more massive body will usually become tidally locked over time. Even if the planet was in the habitable zone, the surface of the tidally locked planet facing the sun would be driven above the boiling point of water. Conversely, the night side of the planet would gradually cool to a few degrees above absolute zero. The expanded atmosphere on the hot side can either be driven into space (if the planet is small with a weak gravity) and permanently off the world or (for a Venus or Earth sized planet) the vapor could carry to the bitterly cold "night side" where it would condense out and freeze.

In Fig 1.11 we see a graph that shows several proposed habitable ranges, and where Earth, Mars and Venus sit, as well as where some tentatively identified exoplanets would sit.

Chapter 2- Orbits

Gravity and Orbital Mechanics

Isaac Newton (1642-1726/27) was one of the scientific and mathematical giants of the 17/18th Century. Among his many contributions were his insights into gravity. In his book titled *Philosophiae Naturalis Principia Mathematica* (A Treatise of the System of the World), he conducts a thought experiment in which he visualizes a Canon on top of a tall mountain. If the earth had no gravity and no atmosphere, and the cannon ball was fired tangential to the surface of the earth the ball would follow a straight line and leave the earth. However, with the effect of gravity, the canon ball would be pulled down. If the canon shell was fired slowly then the Canon ball would hit the ground at Point D. If it was fired faster, it would land at E. Faster still the cannon ball would travel to F. Faster still, the canon ball would never hit the earth but go into a circular orbit. In real life this would not happen because, even on the highest

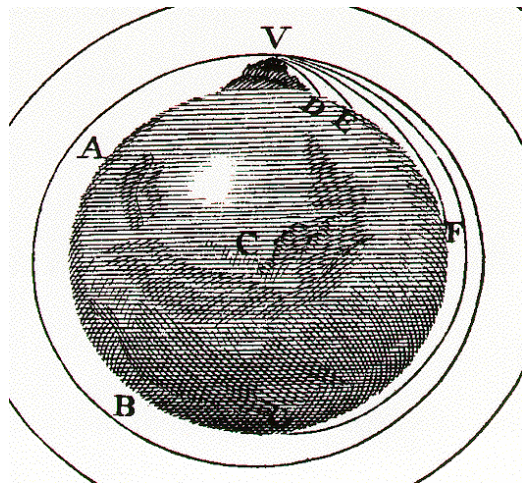


FIGURE 2-1 NEWTONS CANON

mountains, the drag caused by the atmosphere on the canon ball would rapidly slow it down to where it would quickly hit the earth. In addition, if we calculate the speeds required to go into orbit are so large, no gun is powerful enough to launch a cannon ball at the required speed and, even if it could, the force of the acceleration when fired, and then friction with the atmosphere when it left the barrel would be so great that the ball would quickly be vaporized and rapidly decelerated. Regardless, the concept is valid. Rockets can get into orbit by raising above the atmosphere as they accelerate so that when they approach their highest speeds they are already traveling in a near vacuum. In this chapter we will look at orbits and the trajectories objects, including rockets, follow in space.

Newtons Laws

Newtons Universal Law of Gravitation is a simple but powerful formula. It says:

EQUATION 2-1 $F = G \frac{(m_1 m_2)}{r^2}$

Where m_1 and m_2 are the mass of the two bodies attracting each other

$$G = \text{Universal Constant} = 6.672 \times 10^{-11} \frac{Nm^2}{kg}$$

And r is the distance between the two bodies

Another basic equation is:

EQUATION 2-2 $F = ma$

In the case of a falling object on earth it would be subject to an acceleration of 9.81 mps or “g” and the force would be

EQUATION 2-3 $F = -mg$

Making the two equations equal, and specifying m_1 as the mass of the earth and m_2 the mass of the falling body, and rearranging the terms we come up with:

EQUATION 2-4 $g = -\frac{GM_{Earth}}{R^2}$

Where R is the distance from the Earth's center.

The potential energy in a gravitational field will decrease as height increases. The equation for this would be:

EQUATION 2-5 $PE = -\frac{GM_{Earth}m}{r}$

We can see that even though the force of gravity drops off as the square of the distance, the potential energy falls off as $1/r$.

Kinetic Energy is the energy of motion and is described by the equation:

EQUATION 2-6 $KE = \frac{1}{2}mv^2$

Characteristics of Orbits

When a smaller object orbits a large object if traces a path in the shape of an ellipse. Orbits invariably follow an ellipse shape, though they can be very close to a circle—defined by the term eccentricity. An eccentricity of zero describes a circle but this does not occur in nature because the slightest force will disturb the circular orbit into an ellipse. In a circle, the orbital velocity is the same at any part of its orbit. For an ellipse, the velocity will be highest at the lowest point in the orbit—the perigee and lowest at the most distant point, the apogee.

An ellipse is what is called a particular type of conic section. In other words, if you take a plane and intersect a cone, they can take the form of a 1) Circle, 2) Ellipse, 3) Parabola, or 4) Hyperbola.

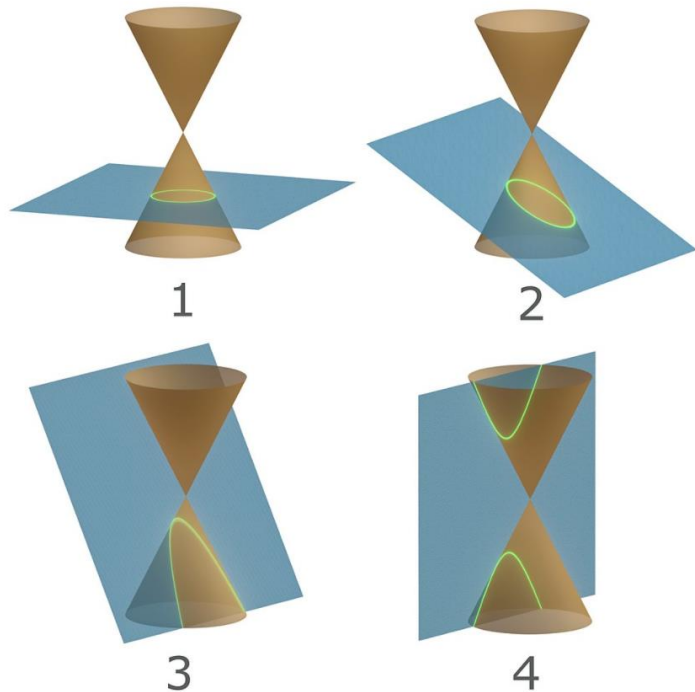


FIGURE 2-2 CONIC SECTIONS

The difference between a Parabolic and Hyperbolic orbit is that, in theory, in a parabolic orbit you will gradually slow down as you get further away until you stop at infinity. A Parabola describes the shape an object travels when it is exactly at escape velocity. If you travel faster than escape velocity, then your orbit is described as hyperbolic.

All orbits are ellipses. In order to describe and calculate orbits it is useful to describe some of the terms. An important characteristic of an ellipse or a circle is that an object in its orbit has the same total energy at every point in its orbit. At the highest point of the orbit (called the apogee) your speed is lowest (i.e., your kinetic energy) but your potential energy is highest. The reverse is true at the lowest point of your orbit- the perigee. The total Kinetic and Potential Energy in an orbit is:

EQUATION 2-7 $E_{total} = \text{Kinetic Energy} - \text{Potential Energy} = K_e - P_e$

EQUATION 2-8 $E = \frac{1}{2}mv^2 - \frac{GMm}{r}$

Where:

M is the mass of the primary object

m is the mass of the orbiting object

G is the Gravitational Constant

v= velocity

r= distance from center of gravitational attraction

Since, in an elliptical orbit any two points of the orbit the total energy will be constant and we can assign these two point two velocities- v1 and v2 and two distances from the center, r1 and r2. Making them equal:

EQUATION 2-9 $\frac{1}{2}mv_1^2 - \frac{GMm}{r_1} = \frac{1}{2}mv_2^2 - \frac{GMm}{r_2}$

Eliminating the common factors, we get

EQUATION 2-10 $\frac{1}{2}v_1^2 - \frac{GM}{r_1} = \frac{1}{2}v_2^2 - \frac{GM}{r_2}$

To simplify, GM is usually shortened to μ . The equation therefore becomes:

EQUATION 2-11 $\frac{1}{2}v_1^2 - \frac{\mu}{r_1} = \frac{1}{2}v_2^2 - \frac{\mu}{r_2}$

So, if we know the velocity and radial distance in one part of our orbit, for any radial distance for another part of our orbit we can calculate a velocity. Note also that the total kinetic and potential energy of the orbiting body is also equal to one half the potential energy of at the average distance a (the semi-major axis)

EQUATION 2-12 $E = \frac{1}{2}mv^2 - \frac{GMm}{r} = -\frac{GMm}{2a} = \frac{m\mu}{2a}$

EQUATION 2-13 $\frac{1}{2}v^2 - \frac{\mu}{r} = -\frac{\mu}{2a}$

RTGEQUATION 2-14 $\frac{1}{2}v^2 = \frac{\mu}{r} - \frac{\mu}{2a}$

EQUATION 2-15 $\frac{1}{2}v^2 = \mu\left(\frac{1}{r} - \frac{1}{2a}\right)$

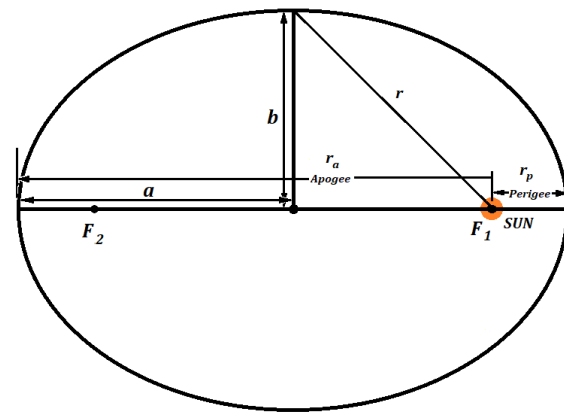
EQUATION 2-16 $v^2 = 2\mu\left(\frac{1}{r} - \frac{1}{2a}\right)$

EQUATION 2-17 $v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right)$

Or

EQUATION 2-18 $v(r) = \sqrt{\left(\frac{2\mu}{r} - \frac{\mu}{a}\right)}$

This describes the velocity of an object at distance r in an elliptical orbit when you know a .



*a: Semi-major axis
b: Semi-minor Axis
F: Focal Points*

FIGURE 2-3 PROPERTIES OF AN ELLIPSE

If we are calculating orbits around the Earth,

then the GM_{Earth} term is usually shortened to μ_e or μ_{earth} . The mass of the earth is approximately $M_{\text{Earth}} = 5.97237 \times 10^{24}$ or:

$$\mu_{\text{earth}} = 398,614 \text{ km}^3/\text{s}^2.$$

For the sun, the mass is so much larger (333,000x) than the earths that the GM_{sun} would be

$$\mu_{\text{sun}} = 132,733,800,000 \text{ km}^3/\text{s}^2$$

Circular Orbits

In a circular orbit an object has not escaped the earth's gravity. Rather it is falling toward the earth but because of its tremendous lateral speed it is falling at the same rate as the earth is curving away. To achieve a low orbit requires a minimal speed for a circular orbit. When describing an orbit, we should remember that a circular orbit is just another type of ellipse. Circular orbits are impossible in nature, the smallest perturbation in an orbit will make an objects orbit an ellipse.

Going back to Newtons' thought experiment where we have a Newton Canon on top of a large mountain. If your shell moved slower than the orbital velocity your canon would be the apogee and you would describe an ellipse where the apogee would be your canon, and your perigee would be inside the earth. Since the earth is solid you would eventually impact the ground. If, instead of the lateral or horizontal motion, the rocket was sent straight up at a velocity less than orbital velocity, the shell would rise to a certain height and then come falling down- after its initial impulse it would immediately start decelerating until it reached the peak of its orbit and then would continue to accelerate at the equivalent of one gravity- eventually impacting the earth at exactly the speed that it was originally fired up at (ignoring the effects of the atmosphere). To place a payload in orbit rockets are sent in the lateral

direction once they are above the denser atmosphere and therefore, while not escaping the earth are traveling so fast that they fall at the same rate that the earth curves away from them.

If we have a circular orbit, then $a = r$ and our Equation 2-18 $v(r) = \sqrt{\left(\frac{2\mu}{r} - \frac{\mu}{a}\right)}$

becomes:

EQUATION 2-19 $v_{circ} = \sqrt{\frac{\mu}{r}}$

Calculating using the value of μ_{earth} we can determine that the earth orbital velocity would be about 7.9kps. Orbital velocities around the sun or any of the planets are substantial. We can easily calculate the circular orbital velocity with these simple equations. Orbital velocity is dependent on only the mass of the objects that are orbiting each other and their separation distance. In most cases, the mass of the planet is so much larger than the mass of the satellite that only the mass of the planet needs to be taken into account.

This velocity calculation for a circular orbit around the earth is a simplification- for a real rocket launched from the earth, other factors come into play to either increase or decrease this requirement. Some of these factors are:

- The earth spins on its axis. The max speed occurs at the equator- but there is some added velocity everywhere on earth except at the poles. At the equator it is maximum- around 1600 kilometers per hour. If we launch from the equator in the direction of the earth spin, we can take advantage of this motion and reduce our launch speed. At a launch site halfway between the pole and equator, it would be only .707 of this velocity, or about 1000 kph. Launching in the direction of the earths spin reduces the amount of Δv needed and therefore allows for slightly less rocket fuel to be carried or allows for a heavier payload.
- Rockets launch vertically. A rocket can waste a lot of energy (fuel) lifting off before it transitions into horizontal flight. Launching vertical will increase the amount of speed needed. Rockets launch vertical primarily due to Drag which is described next.
- Drag. In the lower atmosphere drag can be substantial. Drag is a function of three factors, velocity, atmospheric pressure and the coefficient of drag (C_d - which varies depending on shape). The C_d increases rapidly as the rocket approaches the speed of sound (called the sound barrier). Above the speed of sound, the C_d drops off again. The velocity of the rocket also can influence drag- all things being equal doubling velocity will square your drag if you are in an atmosphere. Finally atmospheric pressure influences drag- if you half the atmospheric pressure you half the drag. By the time the rocket is traveling very fast, it is at a high altitude and the atmospheric density is drastically lower and drag starts approaching zero.

Ellipses and Hohmann Transfer Orbit

In Newtons thought experiment he showed several scenarios whereby the canon shell impacts the earth at further and further distances until it went into a circular orbit. There are two other options that he did

not consider in this example and that is where the velocity is higher than the circular velocity. In this case the object can go into an elliptical orbit with the perigee at the canon, or, if launched even faster, can totally escape the earth's gravitational field. The minimal velocity to escape the earth's gravitational field can be called v_{esc} and describes the shape of a parabola. If an object goes above the minimal escape velocity it will describe a shape called a hyperbola.

Using our formula Equation 2-18 $v(r) = \sqrt{\left(\frac{2\mu}{r} - \frac{\mu}{a}\right)}$

Looking at our diagram of an ellipse we can see that the semi major axis of an orbit (a) is equal to:

$$\text{EQUATION 2-20 } a = \frac{(r_a + r_p)}{2}$$

To find out our necessary velocity at r_p we substitute these into Equation 2-18 we get

$$\text{EQUATION 2-21 } v(r_p) = \sqrt{\left(\frac{2\mu}{r_p} - \frac{2\mu}{r_a + r_p}\right)}$$

Now if we are in a circular orbit, at distance r_p we already showed that: $v_{circ} = \sqrt{\frac{\mu}{r_p}}$

So to go from a circular orbit to a higher elliptical one would be:

$$\text{EQUATION 2-22 } \Delta v = v - v_{circ} = \sqrt{\frac{2\mu}{r_p} - \frac{2\mu}{r_a + r_p}} - \sqrt{\frac{\mu}{r_p}}$$

Or rearranging:

$$\text{EQUATION 2-23 } v(r_p) = \sqrt{\frac{\mu}{r_p}} \left(\sqrt{\left(\frac{2r_p}{r_p + r_a}\right)} - 1 \right)$$

Now this gives us the necessary velocity to get from our lower orbit at the perigee r_p to a higher orbit with an apogee at r_a . Once we get to the higher orbit our velocity will actually be below what is necessary for a circular orbit and left to it own we would drop back down to our r_p so we will need a further orbital velocity bump to go into the new circular orbit. In this case our equation would be:

$$\text{EQUATION 2-24 } \Delta v = v_{circ} - v$$

And our equation at r_a would be

$$\text{EQUATION 2-25 } v(r_a) = \sqrt{\frac{\mu}{r_a}} \left(1 - \sqrt{\frac{2r_a}{r_p + r_a}} \right)$$

Or:

$$\text{EQUATION 2-26 } v(r_a) = \sqrt{\frac{\mu}{r_a}} - \sqrt{\frac{2\mu}{r_a} - \frac{2\mu}{r_p + r_a}}$$

To give an example of how to use this equation, suppose we have a satellite in earths orbit at about 300km. This distance becomes our r_p . The earth has a radius of 6378 km so our satellite is 6678 km from our center. Suppose we wanted to raise our orbit to that of the moons. The earth's moon orbits at a mean distance of 384,400 kilometers. In this example, our r_p is 6678 and r_a is 384400. Substituting,

$$v = v - v_{circ} = \sqrt{\frac{2(398614)}{6378} - \frac{2(398614)}{397456}} - \sqrt{\frac{398614}{6678}}$$

Calculating we get a $\Delta v = 10.884 - 7.726 = 3.108$ kps.

Once we achieved our apogee distance, we would now want to circularize our orbit to stay at this new orbital distance. To do this, at our apogee we would have to add an additional small thrust to get our apogee speed up to what is required to stay in a circular orbit.

$$\Delta v = v_{circ} - v = \sqrt{\frac{398614}{384400}} - \sqrt{\frac{2(398614)}{384400} - \frac{2(398614)}{397456}}$$

$$\Delta v = 1.01832 - .261280 = .75704$$

This sort of maneuver whereby we go from a circular orbit to an ellipse with the apogee at our target

Destination	Orbital radius (AU)	Δv (km/s)		
		to enter Hohmann orbit from Earth's orbit	exiting LEO	from LEO
Sun	0	29.8	31.7	24.0
Mercury	0.39	7.5	13.3	5.5
Venus	0.72	2.5	11.2	3.5
Mars	1.52	2.9	11.3	3.6
Jupiter	5.2	8.8	14.0	6.3
Saturn	9.54	10.3	15.0	7.3
Uranus	19.19	11.3	15.7	8.0
Neptune	30.07	11.7	16.0	8.2
Pluto	39.48	11.8	16.1	8.4
Infinity	∞	12.3	16.5	8.8

distance and then circularize our orbit at the new higher orbit is called a Hohman Transfer orbit.

We can also calculate Hohmann transfer Δv 's from the earth to get to various places in the Solar System and beyond. Here is a table that shows some Hohmann transfer orbits from earth's orbit around the sun (i.e., like a Lagrangian point). In it there are three columns for Δv .³

Note that if we wanted to reach the sun it would require a tremendous Δv - nearly three times greater than to actually reach interstellar targets. The reason of course is that the earth orbits at nearly 30kps and to reach the sun you have to lose all this velocity.

TABLE 2-1 Δv FOR HOHMANN ORBITS FROM EARTH

One other key aspect to much of our discussions in this chapter is that these calculations are dependent on instantaneous (or near instantaneous) application of Δv . In other words, a satellite being raised to a higher orbit will accomplish this through a short burst of rocket thrust. Some rockets are very low thrust

³ In this table, the column labeled " Δv to enter Hohmann orbit from Earth's orbit" gives the change from Earth's velocity to the velocity needed to get on a Hohmann ellipse whose other end will be at the desired distance from the Sun. The column labeled " v exiting LEO" gives the velocity needed (in a non-rotating frame of reference centred on Earth) when 300 km above Earth's surface. This is obtained by adding to the specific kinetic energy the square of the speed (7.73 km/s) of this low Earth orbit (that is, the depth of Earth's gravity well at this LEO). The column " Δv from LEO" is simply the previous speed minus 7.73 km/s.

(for example, electrical thrusters as discussed in Chapter 7) and they would not follow these kinds of trajectories. Instead, they will slowly spiral into a higher orbit. These orbits are much harder to calculate since the thrust is over many weeks, months or even years, all the while the gravitational force of whatever astronomical body we started out from will gradually be reduced, while the mass of the spacecraft will also gradually be reduced as it expels its reaction mass. In deep space, an electrical thruster can get up to substantial speeds, but near a large gravitational body, their performance would be poor, and they frequently take decades to get up to a high enough speed to exit the Solar System. Just as importantly, due to gravitational losses they would consume far more reaction mass than a single large impulse from a rocket.

Escape Velocity

If we have a circumstance where the apogee approaches infinity (the orbit would be in the shape of a parabola), this is called escape velocity. It is the minimal speed required so that the object will never fall back to earth. For this scenario we would put in ∞ for a so using Equation 2-18 $v = \sqrt{\left(\frac{2\mu}{r} - \frac{\mu}{a}\right)}$ and calculating for escape velocity we get:

$$\text{EQUATION 2-27 } v_{esc} = \sqrt{\frac{2\mu}{r} - \frac{\mu}{\infty}}$$

$$\text{EQUATION 2-28 } v_{esc} = \sqrt{\left(\frac{2\mu}{r}\right)}$$

What this equation tells us is that your escape velocity will be always the $\sqrt{2}$ greater than the orbital velocity- or about 44% more. Similarly, if you know the escape velocity the Orbital velocity will be $1/\sqrt{2}$ of the escape velocity for that altitude.

If our interstellar spacecraft were to be assembled into earth orbit it would still be in the earth's gravitational field. However, if the spacecraft were in low earth orbit it would already be traveling at about 7.9 kps, a large part of the required increase in speed. In other words, only the difference in escape velocity to orbital velocity would be needed- or about 3.3 kps. While this would be the minimum additional speed required it must be remembered that since the orbit is in a plane, the advantage of the 7.9 kps orbital velocity at any one time is only in one direction- tangential to the orbit.

In reality, launching a rocket from earth orbit is even more complicated. If the rocket managed to have enough escape velocity to permanently leave the earth, the rocket would still be orbiting around the sun and may not be able to escape the sun's gravity. Appendix E lists some of the planetary parameters as well as escape velocities.

Note that these escape velocities are for objects being launched from the surface of the respective bodies. The sun is a huge body with a very strong gravitational pull. If an object were launched from the sun's surface, to reach escape velocity it would have to achieve the impressive speed of 617.7 kps. However, as you get further from the sun the orbital and escape velocity drops off rapidly. By the orbital distance of Mercury, the escape velocity has dropped to about 67.7 kps. In our case our rocket is even further from the sun- at the earth's orbital distance of 150 million kilometers. At this distance the suns

escape velocity has dropped to 42 kps. Just as it would for an object in earth's orbit, the velocity of the earth in its orbit around the sun already provides a large amount of speed, reducing the needed velocity increase to the difference between the escape velocity and the sun's orbital velocity at the location of the earth. The earth's orbital velocity around the sun is a substantial 29.8 kps, so in theory launching a rocket that is orbiting the sun at the distance the earth does *in the direction of its orbit* reduces the needed Δv to a more manageable 12 kps.

A key point is that when leaving the earth or leaving the sun's gravitational well the speed boost to a spacecraft is maximized only if the rocket is pointed in the direction of its orbital travel. This severely limits the targets that we can send spacecraft to. To maximize the speed boost of the earth motion means objects must go in the same plane of the earth's orbit.

Faster than Escape Velocity

We have established our formula for how fast we need to go to reach escape velocity- but at that speed you are barely breaking away from the gravitational influence... your actual velocity will decrease continuously as you climb out of the gravitational well where technically, if you left at exactly the minimal escape velocity, your speed would approach zero infinitely far away. In practice, you would be going slightly faster than the minimal escape velocity. At some point, the body's gravitational effects become so small that you reach a steady "coasting" speed. How do you calculate this?

The equation is as follows:

EQUATION 2-29 $v_{\infty}^2 = V^2 - v_e^2$

As an example, suppose our V is 12 kps and our escape velocity or v_e is 10. Our final velocity at infinity would be 6.6kps.

Gravitational Slingshot

We have already mentioned how the speed of the object in orbit will be added to the rocket's velocity if the rocket acceleration is in the direction of orbital travel. We can also use the gravity wells of additional planets to add additional velocity to our payload by changing the ship's direction of travel.

When an object approaches a planet, from the point of view of the planet (the planet's frame of reference) it looks like the top example shown in Figure 2-4- the approach velocity and exit velocity are the same. Only the direction has been changed. However, the planet is whipping around the sun, so effectively if you calculate the proper angle and speed of approach your payload can head in the same

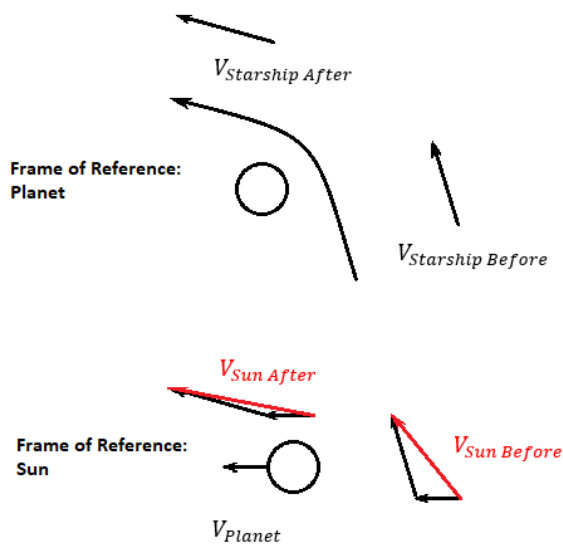


FIGURE 2-4 GRAVITATIONAL SLINGSHOT: PLANET AND SUN REFERENCE FRAME

have approached his truck at 200 kph (truck speed of 100kph plus the balls speed of one hundred) and bounced off at 200 kph. To the kid, he would have thrown the ball at 100 kph but seen it ricochet off the truck at 300 kph. The corollary to this example is shown in Figure 2-6.

To do this with a spaceship, suppose we had one launched radially outward from the sun. This object would decelerate as it climbed away from the sun and eventually reach zero before falling back. Suppose that just as it reaches its close to zero velocity a planet in its orbit comes lumbering along. One can imagine an ideal circumstance where the spacecraft could whip around a full 180deg as shown in Figure 2-6. From a sun perspective the originally unmoving spacecraft would now have a speed of twice that of the planets orbital speed. From Appendix E, if we used Jupiter's orbital speed of 13 kps, the spacecraft could be traveling 26kps. In practice, placing an unmoving object in front of Jupiter is impractical. If such an object was launched from earth, besides having enough energy to climb up the sun's gravitational well and reach out to Jupiter's orbit, you would have to launch backwards to eliminate the nearly 30 kps orbital velocity of the earth.

direction as the planet is traveling- effectively you have added the velocity of the planet to the velocity of the payload as would be perceived by an observer from the sun.

The effect is similar to the case below (Fig 2.5) where you throw a perfectly elastic ball at an approaching tractor trailer. The ball will bounce off the truck and now has its original velocity plus that of the truck. Conservation of energy is preserved as in theory the massive truck will be infinitesimally slowed down while the much lighter ball will accelerate tremendously. The key to this is that from the truck's perspective, the ball would both approach and bounce off the train at the same speed. Suppose our erstwhile pitcher was a real daredevil and standing almost directly in front of the truck when he threw his ball at 100kph. From the perspective of the truck driver the ball would

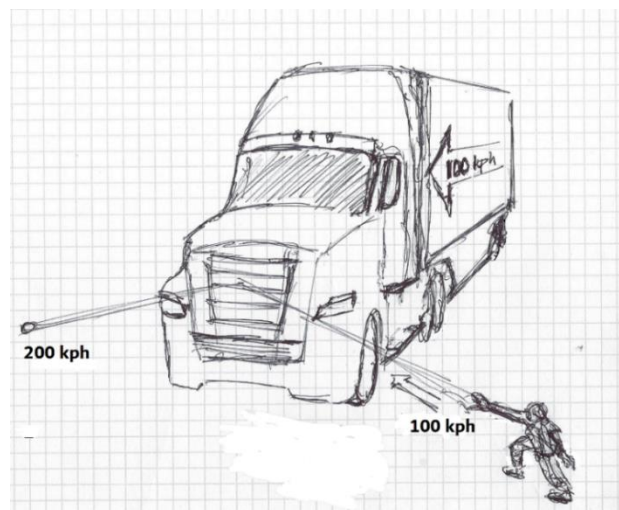


FIGURE 2-5 DAREDEVIL VS THE TRUCK

In the real world, our spacecraft will be climbing up from the sun in a prograde elliptical orbit. At the distance of Jupiter, the orbital speed around the sun is about 13 kps (see Appendix E). If it was correctly positioned the spacecraft would slowly approach Jupiter from below (sunward), get pulled into the planets massive gravitational field, and whip around the planet and head off away from Jupiter 90deg opposite direction from its initial approach. From Jupiter the spacecraft approached at perhaps 2 kps, and left at 2kps. From the sun it would appear that the spacecraft was originally only traveling at around 11 kps around the sun but after it whipped around Jupiter its new speed was 21 kps- or about 10 kps faster. In this case the speed would be the relative approach speed to the planet plus the planet's orbital speed. Multiple NASA missions demonstrate that gains of 10 km/s or more are doable around Jupiter with a course change of close to 90deg.

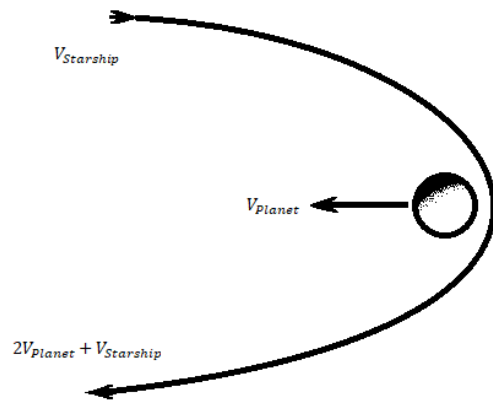


FIGURE 2-6 BEST CASE SLINGSHOT

Figure 2-9 shows the real-world example of the Voyager 2 spacecraft which did a gravitational slingshot past four planets. As you can see, as the spacecraft approached a planet its speed picked up

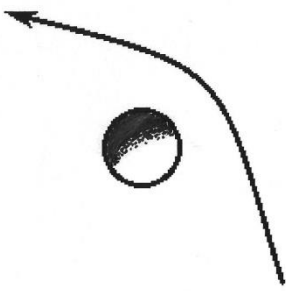


FIGURE 2-7 TYPICAL CASE

tremendously as it was pulled into the planet's gravitational field. After it past the planet its speed would drop off- but because it used the gravitational slingshot effect, its speed relative so the sun always increased- except in the final case of Neptune where the speed actually decreased after the planetary slingshot. Without these slingshots, Voyager could never have left the solar system. With them it is exiting at slightly more than 15kps.

The limitation of the gravitational slingshot is that the maximum velocity increase is along the direction of the planets travel which limits the target stars to the orbital plane (the ecliptic) or very close. In the case of Voyager 2, which did it past four planets, it also depends on the optimum position

for each planet which limits the times when it can be done. Also, as each planet gets further from the sun its orbital velocity is less and there will be less kick to the speed because the planets themselves are orbiting at a slower rate. The importance of staying close to the ecliptic to gain speed becomes obvious when looking at the Neptune flyby which deflected the spacecraft over 45deg from the planet's orbital plane but also reduced its speed.

As shown in Figure 2-6 the maximum practical speed that could be reached would be to an object approaching at high-speed opposite to the planet's direction of travel, whipping around the planet and heading back out in the same direction- exiting tangentially to the planets orbit- but this would be difficult to pull off. Since all planets orbit in the same direction, our Spacecraft, to take advantage of the earth 30 kps speed around the sun, was launched at 10kps in the direction of the earth's orbit- for a

total of 40 kps. If we wanted to approach a planet like Jupiter from the opposite direction, we would have to launch our spacecraft opposite to our planet's direction of travel- or an incredible 70 kps opposite to the rotational movement of the earth. This would be fast enough to counter the earth's 30 kps orbit and give us the equivalent "anti" or prograde orbit speed of 30 kps, plus the 10 kps to put us in an elliptical orbit that intercepts Jupiter. The gain from Jupiter would be far smaller than this huge 70 kps expenditure so it is not practical to maximize our slingshot maneuver in this fashion.



FIGURE 2-8 JUPITER- A POPULAR TARGET TO PERFORM A GRAVITATIONAL SLINGSHOT (PHOTO COURTESY OF NASA)

The earth and all the major planets orbit close to the same orbital plane. The earth's plane is called an ecliptic. In the ecliptic the sun progresses across the 12 zodiac constellations throughout the year as the earth moves around the sun. All the traditional 8 planets orbit in a similar plane around the sun- they are all within a few degrees of the ecliptic which is why all the planets pass through the same 12 zodiac constellations that the sun travels through. To take maximum advantage of the earth's movement along this plane, spacecraft need to be launched along this plane. Also, to take maximum advantage of a

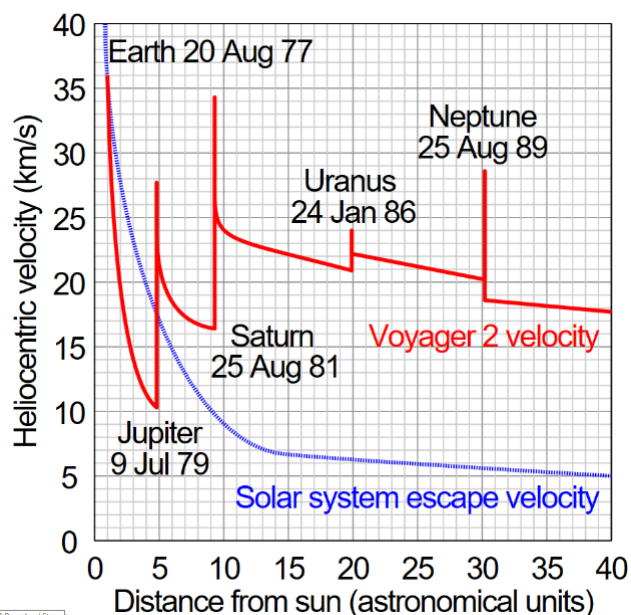


FIGURE 2-9 VOYAGER VELOCITY RELATIVE TO THE SUN (COURTESY OF NASA)

Gravitational slingshot we will need to stay close to this plane- the spacecraft will approach the planet and depart the planet close to the ecliptic to maximize the speed boost. The unfortunate aspect to this is that not many target stars are close to the ecliptic. On our list of target stars, only one is close to the ecliptic- Epsilon Eridian (Figure 2-8). If we want to just change our direction and not go to a star near the ecliptic, we can still use a large planet like Jupiter to redirect us in any direction we would desire. However, the farther away from the ecliptic we are attempting to go, the less of a slingshot boost we would receive from Jupiter (or any other planet) for a gravitational slingshot.

Finally, using the gravitational slingshot can substantially increase our speed- in the case of Jupiter by about 10kps and perhaps somewhat faster if we do multiple slingshots past other planet(s) as long as we remain close to the elliptic.

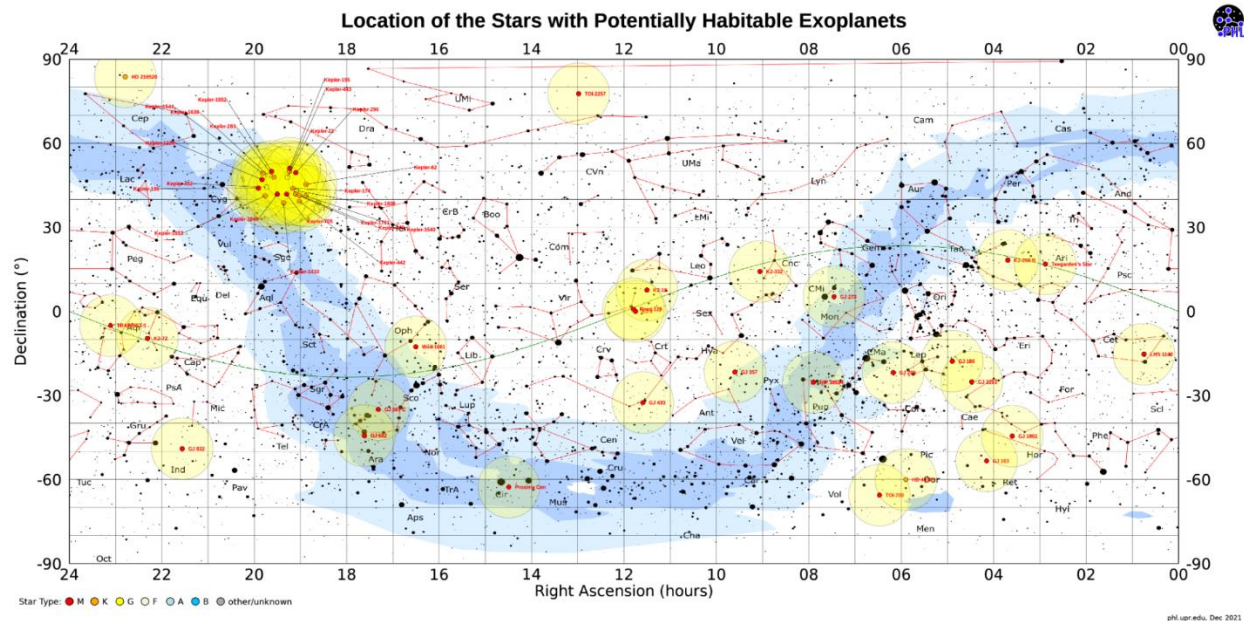


FIGURE 2-10 LOCATION OF NAKED-EYE VISIBLE STARS WITH EXOPLANETS AND THE ECLIPTIC (CORNMELL, 2021); EPSILON ERINDANI IS THE STAR LABELED ERI AND IS LOCATED AT $-3^{\text{h}} 33^{\text{m}}, 09^{\circ} 28'$

Regardless, the speed boost will not be enough to reduce our voyage times to a star by a meaningful amount. There is, however, one more trick up our gravitational slingshot sleeve- that is the Oberth Effect.

Oberth Effect or Powered Maneuver

The Oberth Effect, also called the Oberth Maneuver or just Powered Maneuver is a means of rapidly and permanently increasing velocity. When an object is in an elliptical or hyperbolic orbit, and is descending to its lowest or closet point (called the periapsis) of a large planetary body with significant gravitational field (a sun or planet) as it reaches its closest approach a large force is applied- i.e. a rocket is fired. The effect of this on the ships velocity will often be several times greater than if we just counted on our rocket equation of Δv . The equation is as follows:

$$\text{EQUATION 2-30 } V = \Delta v \sqrt{1 + \left(\frac{2V_{esc}}{\Delta v}\right)^2}$$

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

Using our previous equation for esc velocity:

EQUATION 2-31 $v_{esc} = \sqrt{\left(\frac{2\mu}{r}\right)}$

Recall that $\mu = GM$ and

$$G = 6.672 \times 10^{-11} \frac{Nm^2}{kg}$$

For some representative numbers, the Earth Mass is 5.972×10^{24} kg. The mass of Jupiter is 318 times greater than the earths and the sun is 333,000 time more than the earths.

$$\text{Calculating for } \mu_{Jupiter} = GM_{Jupiter} = 6.6743 \times 10^{-11} \times 318(5.972 \times 10^{24}) = 1.2675 \times 10^{17}$$

$$\text{Calculating for } \mu_{Sun} = GM_{Sun} = 6.6743 \times 10^{-11} \times 333,000(5.972 \times 10^{24}) = 1.3273 \times 10^{20}$$

We need to pick an r. Jupiter has a radius of 71,492 km. We can't approach the planet closer than this without hitting it- hence our radius must be some value greater. The closer we can approach the planet the greater the effect of the powered maneuver will be since our V_{esc} will be greater. For this reason I picked a fairly aggressive approach to Jupiter. The Juno automated spacecraft that was launched in 2011 approached within 4200km from the top of Jupiter's atmosphere or some 75,600km from the planets center. This is closer than any of the moons orbit and well within the faint rings of Jupiter. There are several risks associated with such a close periapsis- the primary one being the intense radiation fields that could damage equipment and astronauts. Effective shielding and the short amount of time spent close to the planet would help mitigate these effects. Indeed, because of the tremendous speeds involved, the time spent close to Jupiter is surprisingly short. Let us see what a powered maneuver can do.

$$v_{esc} = \sqrt{\frac{2(GM_{Jupiter})}{r}} = \sqrt{\frac{2(1.2675 \times 10^{17})}{75,600,000}} = 57,906 mps (57.9 kps)$$

Let us suppose that we are able to apply a 10kps burn at the periapsis. Using this we get the following as V

$$V = \Delta v \sqrt{1 + \left(\frac{2V_{esc}}{\Delta v}\right)} = 10 \sqrt{1 + \left(\frac{115.4}{10}\right)} = 10 \sqrt{1 + 11.54} = 35.4 kps$$

For a delta V of 10kps, we will effectively leave Jupiter's gravitational field going at 35.4kps. Note that the Oberth Maneuver is agnostic to the plane of the orbit- the results are just as good if we approach from any direction. As before, if we wanted to leverage the slingshot effect to increase our speed still further and add the orbital speed of Jupiter from the previously described slingshot effect up to an additional 13 kps but only for stars close to the ecliptic. Even though we would not gain the full effect of the slingshot in any other direction, we may be able to gain a slight boost- another 2-3 kps- and open up many more target stars.

Using the above equations, we can run different scenarios by changing the r distance (which would change the V_{esc}) and the objects mass you are using the Oberth maneuver at. Let us pick four objects to see how the boost will change our final V.

Astronomical body	Mass (earth=1)	Radius of Astronomical Body	Radius (distance at periapsis)
Earth	1	6378	8000
Neptune	17.15	24764	28000
Jupiter	318	71492	75,600
Sun	333,000	696,700	6,900,000

TABLE 2-2

Calculating the Velocity increase using these parameters give us the graph shown in Figure 2-10.

The end results are nothing short of astonishing especially on the lower portions of the graph (a dV of a few kps). One notably characteristic of the graph is that the gains drop off rapidly as you try to increase your dV. Also, despite the large mass of Jupiter (or the sun), the performance gains are somewhat moderate over that of an Earth or Neptune Oberth maneuver. For instance, the performance increase of a powered flyby of the sun is only a little more than about three

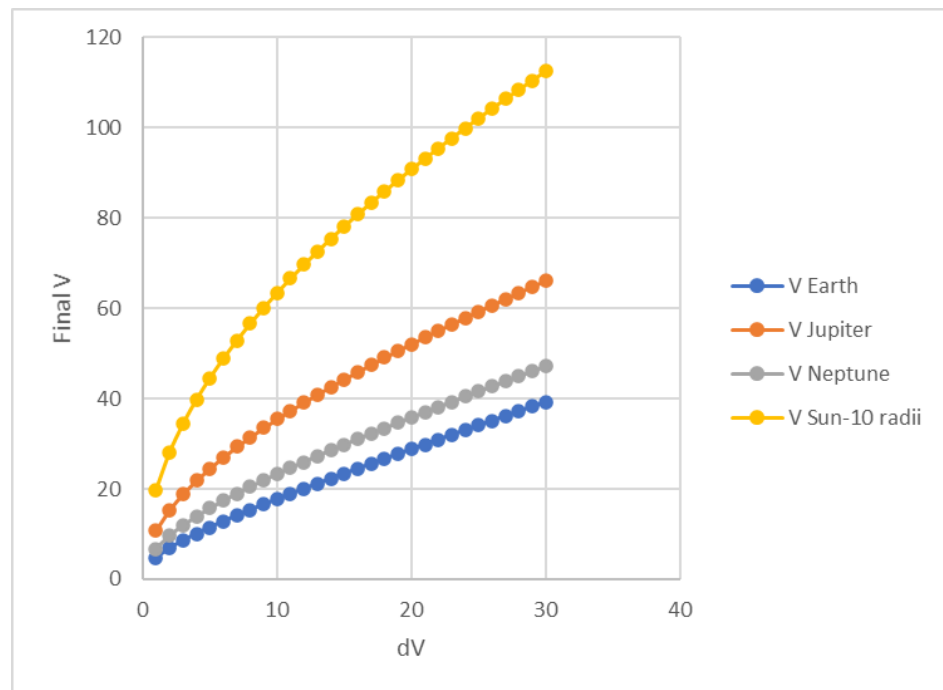


FIGURE 2-11 OBERTH POWERED MANEUVER (NOTE THAT IN THESE CALCULATIONS THE PERIAPSIS DISTANCE FROM THE CENTER OF THE BODY WAS- EARTH- 7000KM; NEPTUNE 28,000KM; JUPITER 75,600KM; SUN 6,757,000KM).

times that of the earth flyby, even though the mass of the sun is 333,000 times more than the earth. This is due to several factors- the biggest is that because the sun is so hot and bloated (about ¼ of the earth's density) we cannot approach as relatively close to the sun center as we can to the earth. I elected to do the powered maneuver at a blazing close 6.9 million km from suns center, or about 10 solar radii from the suns center- but with the earth we approached to within little more than one radii. If the sun were cooler, we could get much closer to one radii. Furthermore, if the sun were as dense as the earth, its diameter would be about 40% less... or closer to 420k kilometers. To a lesser extent the same circumstance applies to Jupiter... its low density is even less than the sun so that even though we are approaching close to its cloud tops the planet is still far puffier than a more solid body like the Earth.

Keep in mind is that these numbers assume an instantaneous application of thrust as the spacecraft reaches periapsis. In reality this is not possible. To maximize the powered maneuver effect, you would have the maximum velocity at periapsis which would be equal to the V_{esc} . On a small planet like earth, where your time frame when you are near the bottom of your orbit, this would be very small- you would be traveling at close to 10 kps. At this rate you would enter and leave the bottom of the earth's orbital well very quickly. In 5 minutes, you

would have traveled 3000 kilometers. To maximize your velocity gain you would likely want to restrict your burn time to perhaps no more than about 5 minutes for a small object like the earth. For more massive planets or the sun your time to apply your thrust would be greater since your time near the bottom of the gravitational well would be much longer, more than enough to offset your greater periapsis velocity.

Finally, you may reasonably ask how is this powered maneuver possible? How are we gaining more speed than we are putting in? Wouldn't this seem to violate some sort of conservation of energy? The answer is that we are not. In Figure 2-11 we see part of the explanation. Normally a rocket is starting off with Scenario #1. However, when we drop toward the sun we pick up tremendous velocity- with a close approach perhaps several hundred KPS. At this close range our v_{esc} will be substantial. Adding our delta V of 10kps would add to this already substantial number. The falling ship is converting its PE to KE as it falls- the full mass of your rocket and fuel is acquiring tremendous KE. When its KE is highest, we eject a lot of rocket fuel mass out the back. KE is a product of v^2 , so even though our rocket mass decreases, any increase in v has a disproportionate effect on its energy and therefore velocity per Equation 2-29:

$$v_{\infty}^2 = V^2 - v_e^2$$

Normally, as the rocket climbs back out of the gravity well some of this KE is converted to PE. But PE is now not the same- the rockets mass has been reduced substantially while our KE has been increased as a square function. The fuels KE was decreased (the rocket exhaust is slower compared to the sun) but it transferred its KE to the rocket.

How rockets actually work will be covered in the next chapter.

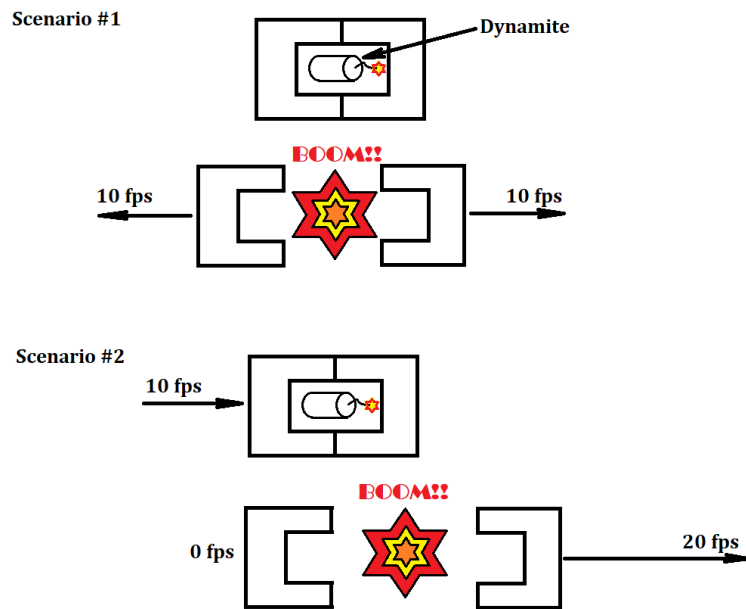


FIGURE 2-12 OBERTH MANEUVER EXPLANATION

Chapter 3- Rockets and the Rocket Equation

Rockets

Rockets are simple (in concept) devices that depend on the famous Newton's law of equal and opposite reaction. In the optimized (i.e., most efficient) engine, the exhaust pressure exiting the rocket nozzle is the same as the ambient pressure around the rocket. In this scenario the rocket has extracted all the available momentum from the exhaust gas. Even though rockets can be described as "simple" that is not to underestimate their design difficulties. They must deal with tremendous forces and temperatures that make their actual construction quite challenging.

The basic calculations for determining the performance of a rocket are straightforward. However, as are many things in real-life, real-world limitations make this simple analysis a little more complicated.

In a rocket you have a combustion chamber where fuel and oxygen mix and combust in a continuous burn. This generates a large internal pressure with only one exit from the chamber. If the exit was a simple hole, the burned exhaust would pile up at the hole and spray out the other side. In this case, there would be motion imparted to the chamber because of the gas spraying out the hole, but it would not be anywhere near as efficient and as forceful if we did a little engineering. The exhaust gas would be very turbulent- much of the exhaust would exit sideways where it would not contribute to the rocket's forward motion. Furthermore, the velocity of the exhaust would be subsonic since the exhaust hole would limit the velocity (but more on that shortly). To direct the thrust in the proper direction, and to maximize its velocity, rockets have well designed nozzles to direct this momentum and maximize the rockets efficiency.

Figure 3-1 shows the forces operating in a rocket and is useful for describing what is going on. In the thrust chamber, fuel and air are mixed and ignite drastically increasing the temperature and hence pressure. The superheated gas has only one direction to go- toward the neck. While it is outside the scope of this book to explain the why's (the book would be very long and boring), the expanding gas accelerates as

it approaches the neck- like what happens when you put your finger partly over the nozzle of a garden hose and the water sprays further because it has been accelerated. As the gas races faster and faster it squeezes into the neck of the motor until it hits the speed of sound. Then an odd thing happens, after the hot gasses pass through the neck, it starts expanding into the nozzle where it accelerates again. It is

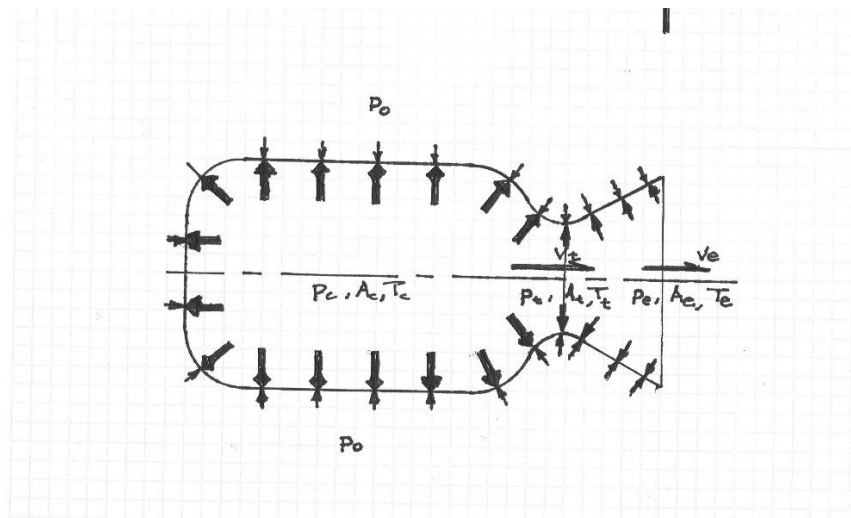


FIGURE 3-1 ROCKET CROSS SECTION WITH FORCES

a fact that if you take gas traveling at below the speed of sound it accelerates as you compress it. Above the speed of sound the opposite happens- if you allow the gas to expand, it will accelerate.

The nozzle also does a second key thing- takes the hot expanding gas and accelerates it in a single direction- directing most of the thrust in the direction opposite to the desired direction of travel.

The actual equations for calculating the thrust are straightforward. In mechanics, force equal mass times acceleration and we have the equation 2-2.

$$F = ma$$

For rockets we call the Force acting on our rocket the thrust. Thrust can also be defined as the change off momentum and described by the equation:

EQUATION 3-1 $F = \frac{dm}{dt} v_e$

Where:

$$v_e = \text{exhaust velocity}$$

The reality is slightly more complicated... the above equation assumes that the full exhaust velocity energy is captured. Some of the energy is lost. The full equation representing the thrust force of a rocket is captured by the equation below:

EQUATION 3-2 $F = \dot{m}v_e + (p_e - p_o)A_e$

Where:

$$p_e = \text{pressure at exhaust}$$

$$p_o = \text{ambient atmospheric pressure}$$

$$\dot{m} = \frac{dm}{dt} = \text{mass flow rate}$$

Rearranging we get

EQUATION 3-3 $F = \dot{m}(v_e(\frac{p_e - p_o}{m})A_e)$

For a perfectly expanded nozzle, where $p_e = p_o$ this reduces too:

EQUATION 3-4 $F = \dot{m}v_e$

Rocket Equation

Tsiolkovsky (b 1857- d 1935) is now a famous Russian scientist that thought a lot about space travel. When he was thinking of these problems, he was not famous and rather poor... he lived most of his life in a log house in the outskirts of Kaluga- a small town Southwest of Moscow. In 1897 he penned what is now his famous equation:

EQUATION 3-5 $\Delta V = v_e \ln \left(\frac{m_0}{m_1} \right)$

Where:

m_0 = 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).

Another variation of this equation is:

EQUATION 3-6 $MR = e^{\Delta v/v_e}$

Tsiolkovsky's work laid many of the mathematical foundations of rocketry but at the time he published them his work was not appreciated. Several other concepts that will be important later were also laid out- including the term of Specific Impulse.

Specific impulse is represented by

I_{sp} = Specific Impulse (a dimensionless term)

and represents the efficiency of the fuel. It represents the Thrust divided by mass flow rate and can be calculated by:

EQUATION 3-7 $I_{sp} = \frac{F}{\dot{m}}$

Rearranging this to get thrust:

EQUATION 3-8 $F = I_{sp} \dot{m}$

Additional useful equations are:

EQUATION 3-9 $I_{sp} = \frac{v_e}{g_o}$

EQUATION 3-10 $v_e = g_o I_{sp}$

Where:

$g_o = 9.81 \text{ mps}^2$ = the acceleration of gravity on earth

Taken together, these equations tell us a lot about rockets. Equation 3-5 tells us is that the final speed of our rocket is only dependent on two variables- the mass ratio and the effective exhaust velocity- and that's it! To go very fast we need either a high mass ratio or a very fast exhaust velocity. To begin with, lets plot the natural log of various mass ratios vs multiple of V_e :

In this graph we can see that our velocity does increase as we increase our mass ratio- but that the relationship is not linear but exponential. Our mass ratios can quickly become astronomical with little gain in final velocity.

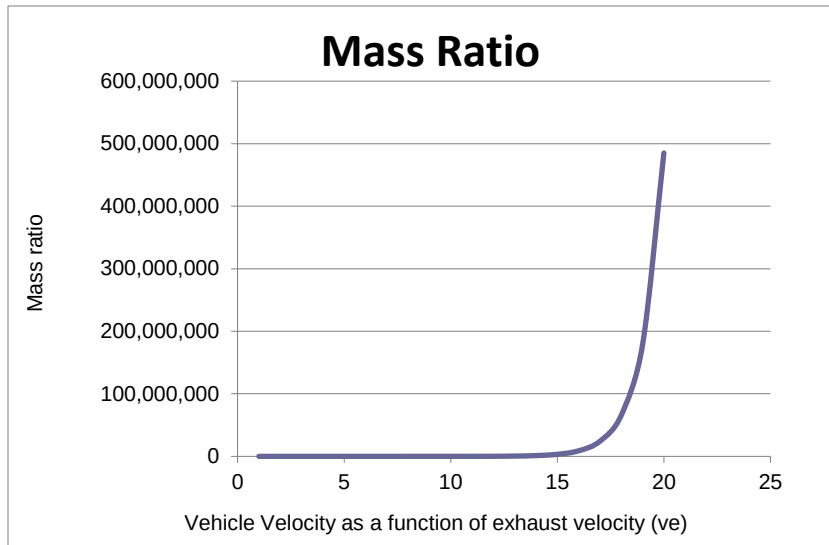


FIGURE 3-2 MASS RATIO VS VEHICLE FINAL VELOCITY AS A FUNCTION OF EXHAUST VELOCITY ZERO TO 20

In a simple case, if we wish to have our rocket go 20x faster than our exhaust velocity, the mass ratio would be over 485 million to one. In other words, to have a 1kg empty rocket, 485 million kg of reaction mass (the exhaust from burning fuel and oxygen) would be needed.

From an engineering perspective, building a rocket of 485 million kg but having an empty weight of only 1kg is borders on the impossible- at least with foreseeable technology. That 1kg would have to include both the

payload, rocket engine and the fuel tanks! Therefore, let's zoom in on a more reasonable target- a rocket that goes 5x faster than its exhaust velocity.

As we can see, even going 5 times faster than the exhaust velocity requires the rocket to be more than 99% fuel. In practice building a rocket that is 1% payload and structure and 99% fuel has never been done. The normal range for a typical rocket launched from earth is 90%-95% of the vehicle's total mass is fuel with the rest being the rocket's structure and payload.

Even this ratio can be a challenge and requires careful engineering and close tolerance. The need for a light structure to carry a lot of fuel drives rocket engineers to frequently use materials like aluminum or composites. It also one of the main reason rocket engineers use staging. Staging improves the performance of the rocket for several reasons.

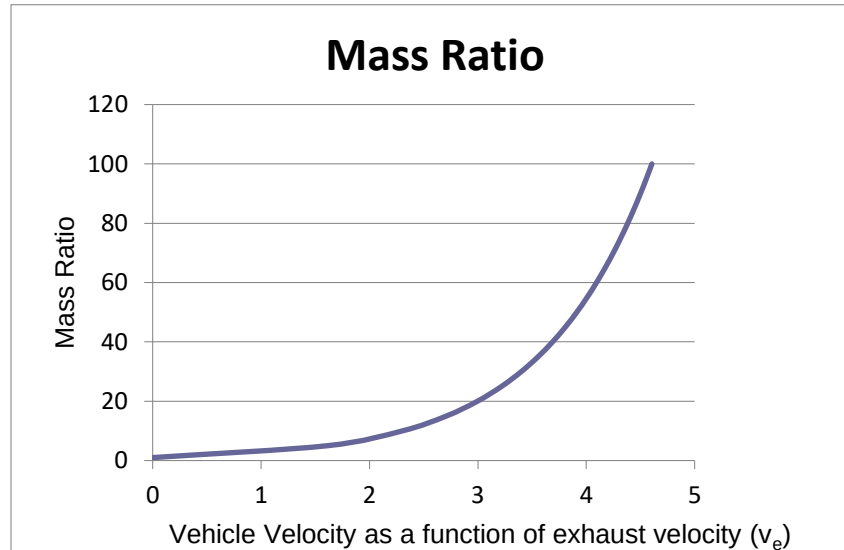


FIGURE 3-3 MASS RATIO AND VEHICLE FINAL VELOCITY AS A FUNCTION OF EXHAUST VELOCITY FROM ZERO TO 5

The Advantages of Staging

All current rockets depend on staging to get a payload into orbit. Why is that?

For one, rocket engines, or specifically their nozzles, are optimized for a specific altitude. At lift off, a rocket engine designed to operate at altitude will perform worse than an identical rocket engine designed to operate at sea level and vice versa. With staging, the rocket stage operates at the altitude it was designed for. Typically, the engines for the first stage are optimized to work at the pressure at Sea Level. As it ascends, its performance will improve slightly but never be as good as one designed specifically for a higher altitude. Therefore, when the first stage is dropped, the second stages engines will be more efficient since its engine nozzles were designed for that higher altitude.

Another issue is that on lift off you need very powerful rocket engines to get off the ground quickly to minimize gravity losses. Additionally, as the fuel is consumed your rocket will get lighter and start to accelerate faster and faster, possibly causing structural damage from the stress and at the very least making it very uncomfortable for your passengers. As we get higher and have less mass, we need a lot less thrust. Staging is a way of getting rid of these overly powerful and heavy engines (as well as your now empty first stage fuel tanks).

A third advantage to Staging is to address an issue we mentioned earlier in this chapter- it is easier to build. Chemical rocket fuels usually have exhaust velocities in the range of 2.5-4.5kps. To get into orbit you need about 8kps- or about 3x more velocity than our exhaust velocity. Using the rocket equation, we can see that to get this performance we can only have our rocket empty mass (including payload) of 5%- essentially 95% is fuel. From an engineering and design perspective this is challenging- the fuel tank for such a large amount of fuel may be over our allocated 5% budget. With staging you not only drop the large fuel tanks needed for your first stage ascent, but also the heavy engines no longer needed. Your remaining stage(s), including the storage tanks and engines, are a lot smaller and less massive.

Having a multistage rocket makes the design less challenging, though it does not help with your payload to orbit- witness the Saturn V which got only about 4% of the starting mass to orbit. It would be very hard to design a single stage rocket with a MR of 25 that was able to perform both at low altitude with a ground lift off as well as to get into orbit with a useable payload. Indeed, it has never been done.

The Tyranny of the Rocket Equation

Besides the mass ratio issues, the rocket equation also tells us that for a fixed mass ratio the final velocity is directly and linearly related to exhaust velocity. Based on this the only way to have an extremely fast ship for a particular mass ratio is to have a very high exhaust velocity. Now, to have our rocket go 20x faster, all we would need is an exhaust velocity 20x more!

Unfortunately, this is simpler said than done. The problem is ultimately one of energy. Normal chemical reactions are limited by how much energy they can release which restricts how hot they can get, and therefore how energetically the rocket exhaust expands. Remember the rocket works by propelling its stored mass in the opposite direction that you want to travel. Unfortunately, the energy equation tells us that to double the exhaust velocity you must square the energy. If we wanted to expel our exhaust mass 20 times faster, we would require 20^2 or 400 times more energy.

With chemically fueled engines, the burning of fuel by breaking chemical bonds, while energetic, only can provide so much energy. For Hydrogen and Oxygen, one of the most energetic fuels we can use, the I_{sp} typically will top out at little more than 450

seconds. To go faster, we will need more energy (higher temperature would increase the combustion chamber pressure) than can be provided by the oxidizing of hydrogen fuel. There are only limited sources able to that have more energy (and hence heat) to choose from- primarily nuclear fission and nuclear fusion. Even though these sources of energy are much more energetic than chemical reactions (by several orders of magnitude) they are harder to control and require complicated and heavy

equipment. Even they are hard pressed to provide the energy to go at a sizable portion of light speed. One of the biggest challenges is building materials that can handle the tremendous heat and energy involved with fission or fusion engines.

Let us, for argument's sake, have a rocket with a payload to mass ratio of 5%. Furthermore, suppose we wanted to build a rocket that is able to achieve 10% of light speed – or about 30,000kps (light travels at about 300,000kps). What would exhaust velocity need to be? Using equation 3-5:

$$\Delta V = v_e \ln \left(\frac{m_0}{m_1} \right)$$

And rearranging the terms we come up with:

$$\text{EQUATION 3-11 } v_e = \Delta V / \left(\ln \left(\frac{m_0}{m_1} \right) \right)$$

$$v_e = \frac{30,000}{\ln(20)}$$

$$v_e = 10,000kps = 10,000,000mps$$

This works out to an specific impulse of about 1 million! Chemical fuels such as those used by the Saturn V rocket, have V_e speeds only a fraction of this- on the order of 3000-5000 mps (3-5 kps).

To revisit what a high exhaust velocity means for the energy requirements, consider the formula for Kinetic Energy or K_e from Equation 2-6:

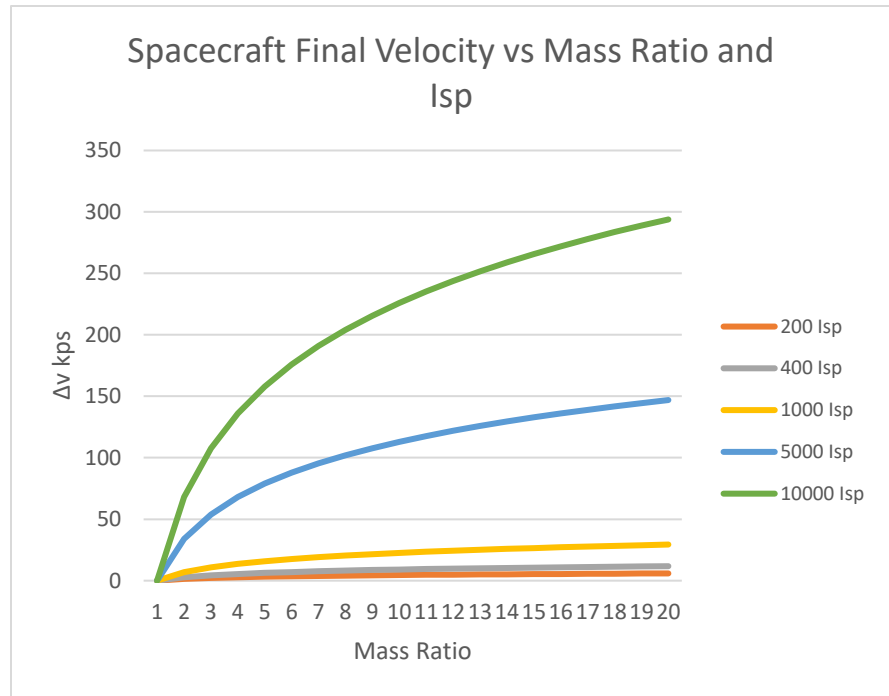


FIGURE 3-4 ΔV VS MASS RATIO WITH DIFFERENT SPECIFIC IMPULSE

EQUATION 2-6 $K_e = \frac{1}{2}mv^2$

In the case of the V_e of 10,000 kps considered above, this is on the order of 2,000x faster than a typical chemical engine of 5kps. Because of the equation for Kinetic Energy, the power required to generate this velocity would be $2,000^2$ or 4 million times more than a typical chemical rocket provides! This is a large engineering challenge as our design would have to be able to handle these tremendous energies without melting or blowing apart. Also, what frequently happens with higher specific impulse engines is that as the velocity goes up, the mass ejected per second goes down to keep the energy requirements (usually heat) reasonable. This leads to the somewhat counterintuitive effect that the most efficient rockets (highest exhaust velocity) usually have very low thrust.

Rocket Design in Real Life

Rockets when launched from the surface of the earth face several challenges:

1. Friction with the atmosphere. This has several undesirable effects:
 - a. Atmospheric Drag
 - b. Friction induced heating
 - c. Aerodynamic stress
2. Gravity Loss
3. Engine Efficiency considerations

Friction with the atmosphere:

Atmospheric Drag

Atmospheric Drag- One of the reasons rockets are launched vertically is so that they can quickly get to a higher altitude where the atmosphere is considerably thinner (as can be seen in Figure 3-6) and you encounter less drag. Drag is caused by friction between your rocket and the air molecules.

At a particular pressure (i.e. altitude) drag on a rocket increases rapidly as your speed increases and has a spike as you approach the speed of sound (the so called Sound Barrier) (See Figure 3-5). The force of drag can be calculated by the following equation:

EQUATION 3-12 $F_D = \frac{1}{2}\rho\mu^2C_D A$

ρ = mass density of fluid

μ = flow velocity relative to object

A = reference Area

C_D = the drag coefficient – a dimensionless number particular to the object

Even though the Drag Coefficient C_D is different for different shaped objects its overall profile is similar. Figure 3-5 is typical. The C_D will remain constant or slightly increase until you approach the speed of

sound (though drag nevertheless increases due to the flow velocity). As you approach the speed of sound (also called Mach 1) the C_D literally takes off- spiking around or slightly above the speed of sound. This is the famous sound barrier that needed to be “broken”. Finally, as you go substantially higher than the speed of sound the C_D gradually drops off.

The Drag Coefficient is fixed by your objects shape and its orientation in space, but the drag force (F_D) is affected by two other variables- your speed and the atmospheric pressure. You are somewhat hamstrung by your need for speed- to get into orbit you need to go very fast which would imply a very high drag. Rocket engineers avoid the worst of this by getting to a higher altitude where the atmospheric pressure is minimal before the rocket starts ramping up its speed. An engineer tries to optimize two conflicting goals - to get to a higher altitude quickly to minimize the gravity losses, but not too quickly so as to approach the speed of sound at a low altitude where a high p and a high C_D will increase your drag.

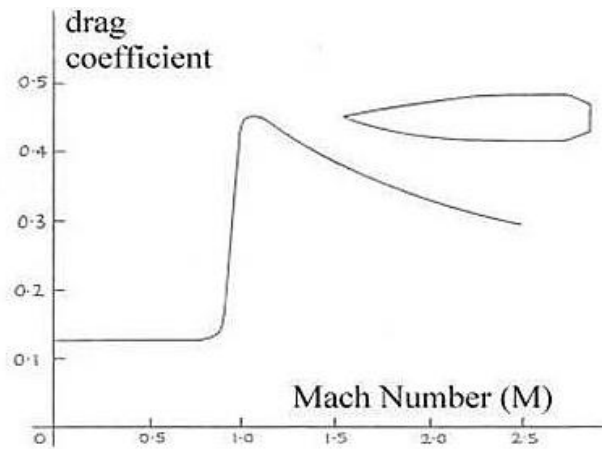


FIGURE 3-5 DRAG VS MACH NUMBER

Minimizing drag has two advantages, it avoids unnecessarily wasting fuel, but also, the drag adds a lot of stress to the rocket (more on that shortly).

Fortunately, when rockets are first launched near sea level they travel very slowly, and the air resistance is relatively small. As they climb and approach the speed of sound the atmospheric pressure has already started dropping, making the drag increase less than if the rocket tried to break the sound barrier at sea level. Nonetheless the tremendous increase in drag that accompanies your increasing speed while still at low altitude increases the maximum structural stress on the rocket. This point is called max Q. During spacecraft launches, max Q is one of those points where everyone breathes a sigh of relief when passed.

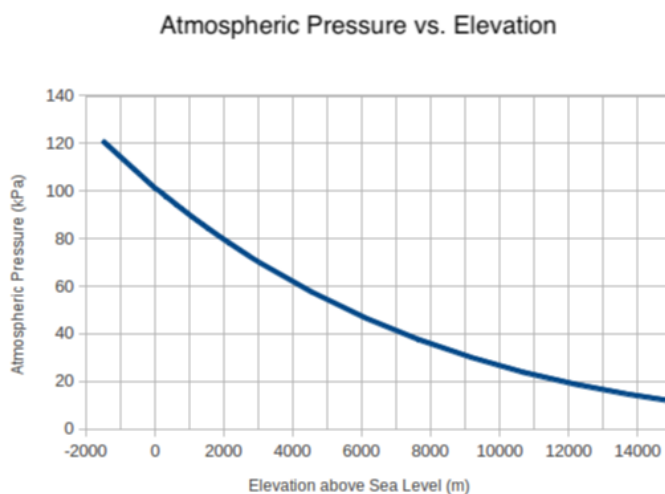


FIGURE 3-6 ATMOSPHERIC PRESSURE WITH ALTITUDE

A good approximation of atmospheric pressure can be derived from the ideal gas law. Graph of atmospheric pressure vs altitude looks like Figure 3-6.

As can be seen from the chart, if atmospheric pressure is 100 kPa at sea level, at about 6000 meters it is below 50 kPa. Mt Everest is about 8848 meters tall- at this altitude pressure would be less than a third of the pressure at sea level.

Fortunately, space is essentially a vacuum, so that resistance and friction are virtually non-existent.

This allows a rocket to travel friction free. It also is the reason why most movies are inaccurate. In deep space, a spacecraft whose engine shuts down will not slow down because of friction. It will continue to travel in the same speed and path as determined by Newtons laws of motion.

Friction and compression induced heating

When discussing rockets, the velocities, even if small compared to the speed of light, are still huge. On earth, vast speeds are almost impossible to achieve because of the friction generated against the skin and the compression of the air in front of the rocket which causes both heat and drag. At very high speeds the atmosphere acts almost as a solid wall. If a rocket were to travel near sea level much more than 3 or 4000 kilometers per hour the friction and compression heating of the air in front of the rocket would quickly heat the outer surface of the rocket to over a thousand degrees Centigrade. In general metals gradually weaken as the temperature increases until they finally have no strength left and start melting. Aluminum will melt at 660° C but will weaken considerable before then. Other materials melt at higher temperatures. Different grades of steel and stainless-steel melt at different temperatures but usually range is between 1350° C and 1450° C. Titanium melts at an even higher temperature of nearly 1800° C and as a result is sometimes used on the leading edges (where frictional heating is highest) of high-speed aircraft. A rocket operating at low altitude and a fast speed would quickly burn up regardless of the metal used. A space capsule may experience up to 1650 °C on reentry to the earth's surface- but can handle it because of the specially designed ablative materials used and the relatively short time the capsule is exposed to the high heat load.

It should be noted that friction and compression induced heating are different. Most times, when we talk about a high-speed aircraft, there is considerable skin friction where the heat is generated by the friction of the atmosphere over the rapidly moving skin. For rockets the reality is that most heat is generated by compression heating. For a streamlined aircraft much of this heat will be at the nose, where a shock wave will form at the tip. That is why the noses of high-performance aircraft or missiles are frequently made of high temperature materials like titanium. This configuration works for objects that are going at a few times the speed of sound. As your speeds get higher (say Mach 20) the temperature would rapidly increase to temperatures higher than any material could tolerate. For objects traveling very fast, like reentry capsules approaching the earth, engineers design a blunt frontal shape. Besides increasing drag (which we usually want during reentry so as to slow your ship down), this configuration produces a compression shock wave, but the wave is detached from the surface of the spacecraft, reducing the heat flux that would occur if the shock wave was in contact with the skin.

Drag induced Stress

In the Drag equation the factor $\frac{1}{2}\rho\mu^2$ is also called dynamic pressure and is referred to as Q. During the ascent of the rocket as μ^2 increases as the atmospheric density, ρ , is decreasing. There is a point where the Q value is maximum, and this is called Max Q. This, combined with your Drag coefficient, is why the rockets throttle back and slow down their acceleration as they approach Max Q. Breaking the sound barrier and Max Q are usually close to each other- and both are minimized by lower ρ . Max Q and the sound barrier together cause not only additional stress on the rocket but tremendously increased drag which wastes fuel. At higher altitude this drag rapidly drops off so as soon as you are past max Q your drag and stress decrease and you throttle up.

Gravity Loss

All rockets spend a lot of their energy just lifting off vertically- before the rocket tilts into a horizontal direction. The vertical direction basically does not help us gain any speed at all but it is done for several reasons. One is the item discussed previously- you want to be at altitude so you can get quickly into the thinner air where your drag losses are minimized, you waste less fuel, and your friction heating and your dynamic stress are reduced. From a safety perspective, you also want to be up at altitude if something goes wrong. Only when you reach a high altitude can you start rolling the rocket horizontally and start gaining speed like mad.

While launching vertically allows you to get out of the dense atmosphere quickly, it does not help you gain horizontal speed which is what you need to achieve orbit. All the time spent climbing vertically is wasted energy that will not help you achieve orbit. For this reason you want to accelerate as quickly as practical while ascending vertically but not so quickly as to approach max Q at a very low altitude. The trajectory a rocket follows is a trade off between efficiency and stress loads.

To give you an extreme example of gravity loss imagine your rocket has a thrust exactly equal to its weight. In this case the rocket will burn a lot of fuel but not accelerate at all- or rather its acceleration is exactly equal (but opposite) the acceleration of the earth's gravity. The rocket will just hover. As it burns off fuel, assuming its thrust stays the same, the rocket will slowly start rising as it gets lighter. A lot of energy (fuel and oxidizer) is being used to keep the rocket from falling back to earth. The excess of thrust over weight is the part that accelerates the rocket and causes it to start rising. The only way to reduce gravity loss is to get it up to altitude as quickly as possible and then rotate horizontally. In most scenarios gravity loss accounts for a 10% or so loss of theoretical performance.

Engine Efficiency Considerations

When we discuss rockets in the real world that are launched from the surface of the earth, they do not have the performance that the rocket equations would indicate. There are several reasons for this.

Nozzle Design

There is only a single ambient pressure the engine nozzle is designed for. Since the rocket is changing altitude as it rises the surrounding ambient pressure will drop. A rocket engine nozzle is usually optimized to be somewhere in the middle of the pressure it will operate in.

When the rocket fuel and oxidizer mix in a rocket engine it burns rapidly, drastically increasing its temperature and pressure. In a rocket, this combustion chamber has only one exit that narrows down to the throat. When a gas (or liquid) travels at subsonic speeds through a reducing space, it will accelerate. In a properly designed rocket, the gas speed will reach supersonic speed at the narrowest area (the throat). It is a thermodynamic property of gases and liquids that at supersonic speeds the opposite effect occurs- as the area expands after the throat the velocity increases. At supersonic speeds, as the nozzle area increases, the gas expands and increases its velocity while the pressure (and temperature)

drops. A rocket will operate most efficiently when the exhaust gas coming out of the nozzle is at the same pressure as the surrounding ambient pressure.

For example, the space shuttle main engines (SSMEs) had to operate from sea level to a vacuum. At sea level its nozzles were overexpanded- the atmospheric pressure is higher than the exhaust of the rocket. Overexpanded means exactly what it sounds like- the Nozzle is larger than it needs to be causing the exhaust to expand more than it should- dropping its pressure to below that of ambient. The ambient pressure will try to push back into the nozzle. Normally the practical impact is that this will compress the exhaust gas (leading to the shock diamonds that you can see in the exhaust) and reducing the engine efficiency. When the exhaust is overexpanded, the thrust is provided by Newtons law of equal and opposite reaction MINUS the pressure differential across the exit plane of the nozzle.

As the shuttle rose in altitude the atmospheric pressure dropped and the situation changes- from being overexpanded the engine exhaust will gradually equal the atmospheric ambient pressure. At this stage the engine directly follows Newton law of equal and opposite reaction, and the nozzle is perfect for the pressure it is operating at.

But the shuttle would continue to rise until it was in the vacuum of space. Now the ambient atmospheric pressure is LESS than the exhaust. As soon as the higher-pressure exhaust exits the nozzle it will flare out. In this case the nozzle is underexpanded- it is not optimized nor extracted all the available momentum from the hot gas. Some of this is recovered by the fact that there is now a differential pressure across the exit plan that (as opposed to the overexpanded exhaust) and this positive pressure is now added to the thrust.

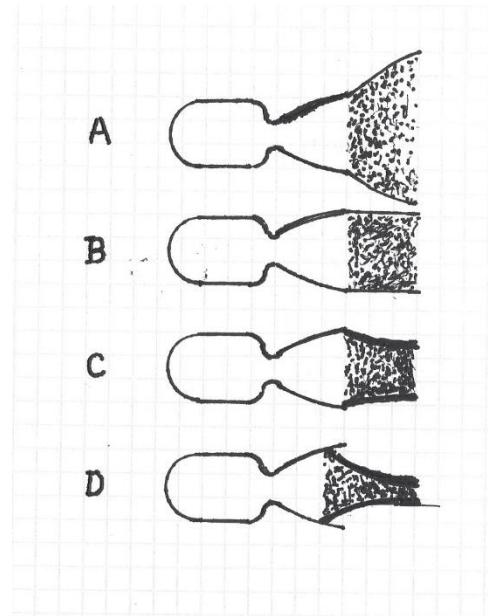


FIGURE 3-7 ROCKET NOZZLE

- A- Underexpanded
- B- Ambient
- C- Overexpanded
- D- Grossly Overexpanded

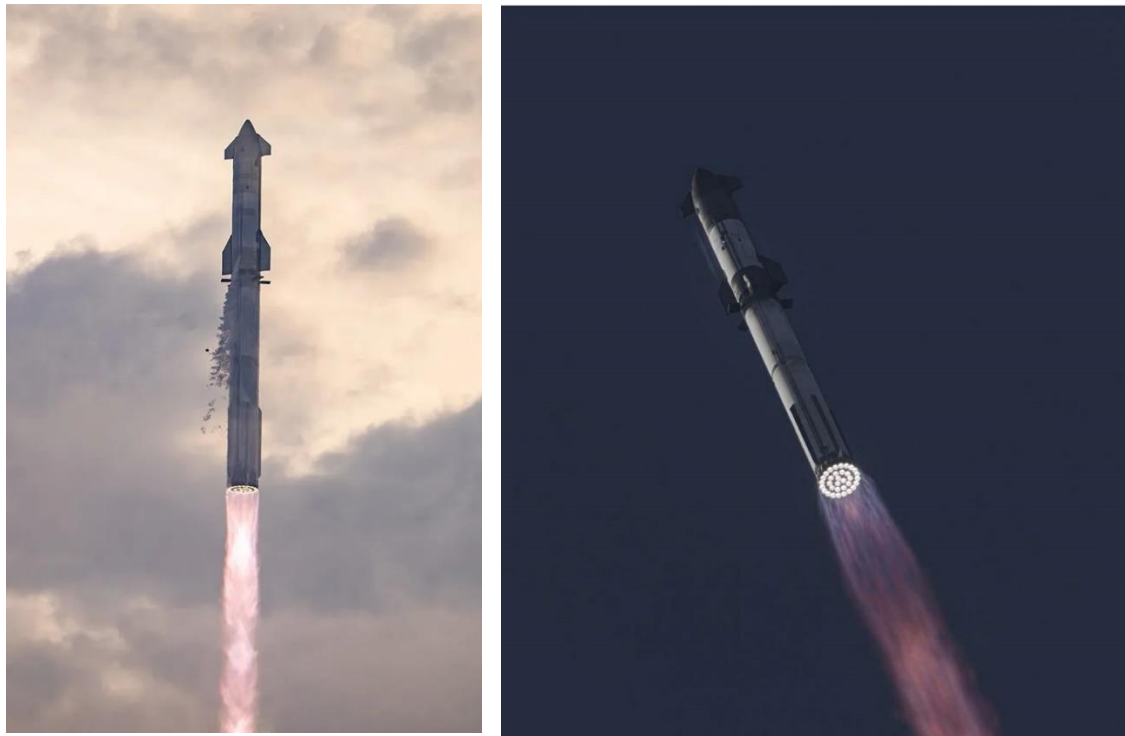


FIGURE 3-8 STARSHIP AT SEA-LEVEL (LEFT) AND AT ALTITUDE. NOTE THE EXHAUST PLUME IS NARROW AT SEA LEVEL, INDEED IT NECKS DOWN A BIT, INDICATING OVEREXPANDED EXHAUST. AS THE STARSHIP GAINS ALTITUDE THE PRESSURE DECREASES AND THE EXHAUST STARTS SPREADING OUT- THE EXHAUST IS NOW UNDEREXPANDED.

Specific Impulse in the real world

Earlier in this chapter we explained the rocket equation. The rocket equation is simple and connects the Effective Exhaust Velocity (v_e) and the mass ratio of fuel and total mass to a final velocity. Remember that V_e is different for every rocket and is a function of several factors- primarily chamber pressure (i.e. temperature), molecular weight of the combustion products and Nozzle design. In general, v_e is directly related to the square root of the exhaust temperature divided by the molecular weight. Also, as discussed, the V_e will change as the rocket changes altitude- increasing as the surrounding pressure decreases.

Rockets are designed with certain performance characteristics based on the fuel being used, the size of the rocket, where it will be operated (sea level or space), reliability and costs. If we want to calculate how fast our rocket will go with need to determine what our Effective Exhaust Velocity is and what our mass ratio is. Assuming the engine combustion chamber and nozzle is optimally designed the Effective Exhaust Velocity is determined by only two factors, the energy released by the combustion and the molecular weight of the exhaust/combustion products. The exhaust products are determined by the fuel used (and in rare cases the oxidizer if pure oxygen is not used). One reason that the I_{sp} for LH/LOX is so high is that the exhaust product is water, which has a relatively low molecular weight of 18. If for some reason LH/LOX produced some other exhaust product that was heavier, its v_e would be lower. Rockets that use Methane, as well as Kerosene related fuels have much heavier exhaust products and therefore lower performance even if the temperature were equal. V_e is related to specific Impulse by Equation 3-7:

$$v_e = g_o I_{sp}$$

To calculate Specific Impulse I_{sp} we just rearrange the terms of the equation to:

$$\text{EQUATION 3-13} \quad I_{sp} = \frac{v_e}{g_o}$$

Below is a Table 3-1 of some of the more popular and common rocket I_{sp}

Rocket	Propellant	Specific Impulse (I_{sp}), Sea Level	I_{sp} , Vacuum
Space Shuttle Main Engine RS-25	LH2/LOX	366	453
Saturn V F-1	RP-1/LOX	263	304
Saturn V J-2 (second Stage)	LH2/LOX		421
Merlin 1D	RP-1/LOX	282	311
Raptor	CH4/LOX	330	380
BE-4	CH4/LOX		??? Still in development
RD-180	RP-1/LOX	311	338

TABLE 3-1 VARIOUS PROPELLANTS AND THEIR SPECIFIC IMPULSE (I_{sp} 's) AT SEA LEVEL AND ALTITUDE

As you can see, there are different specific impulses at sea level and at altitude for each rocket. In this chart and throughout this book LOX means liquid Oxygen- which is our oxidizer, and for fuel, LH2 or LH means liquid Hydrogen, RP-1 is a very refined Kerosene, and CH4 is Methane.

Going back to equation 3-2, let us look a little more at what the rocket force equation means.

$$F = \dot{m}v_e + (p_e - p_o)A_e$$

The first part of the equation is simply the mass flow times the exhaust velocity. The other is an extra thrust that is the excess pressure at the end of the Exhaust Nozzle over the ambient pressure. For an optimum engine design, the exhaust nozzle pressure would be exactly the same as the ambient air. In this case, the equation would only have the first component.

If the nozzle shape is fixed and the engine operates from sea level to vacuum as is the case for the Space Shuttle, the Specific Impulse noted in the table above is accurate. However, if the shuttle used a vacuum optimized engine, then its I_{sp} at altitude would be even higher... but the exhaust nozzle bell would be longer, larger and heavier. In addition, the added expanded bell nozzle at Sea Level would likely mean a severely overexpanded nozzle which would have a lower I_{sp} than 366.

Energy and Power

The rocket equation is used in calculating a rocket's performance. Based on two parameters, the exhaust velocity, and the mass ratio, you can determine the rocket's increase in speed. The mass ratio is a straightforward number. The exhaust velocity is more subtle. This number is pretty much driven by the pressure achieved in the combustion chamber, the atomic mass of the combustion products and the efficiency of the exit nozzle. There are practical theoretical limits to a rocket's ultimate Specific Impulse driven by the how energetic the burning is of a particular fuel along with the molecular weight of the exhaust products. Most modern rockets operate near their theoretical limits. Why is that?

Exhaust velocity, whether liquid rocket fueled engine, a nuclear thermal engine, or an electric engine is determined by energy or power. The more energy that is put into the system, the faster the exhaust velocity will be.

The rockets final speed is ultimately determined by how much energy is imparted to the exhaust mass and how efficiently it is applied. In a normal chemical rocket, the efficiency is surprisingly high- frequently over 90%. All engines, whether chemical, nuclear thermal, electrical do not operate at 100% efficiency. A chemical rocket engine usually converts up to 95% percent of its energy to thrust. However, electric engines that are driven by nuclear power generators frequently convert only a small portion of their thermal power to thrust. A big contributor to this loss of efficiency is in the actual generation of power- only a portion of the generated power is able to be delivered to the engines and the rest is "waste heat". The most common nuclear power supplies used today, called RTU's, are below 10% efficient in converting their thermal heat to useable electricity. The rest is just waste heat.

Even after we generate our power, additional inefficiencies arise as we convert our power to thrust. In the case of the electric powered ion engine efficiency looks to be about 65-80%. Combined with our power supply efficiency, we may only convert 30-40% of our power to useable thrust.

Chemical reactions only produce a fixed amount of energy per mass- basically the temperature of the gas. If I mix the proper ratio of Hydrogen and Oxygen, I will always get the same amount of energy per mass of oxidizer and fuel. Once my energy per kg is fixed, I can only increase my vehicle speed by using more fuel- increasing the mass ratio.

In addition, the energy required to increase the exhaust velocity is an exponential function. Energy follows the Equation 2-6 we mentioned earlier when discussing the energy of orbits and the energy of exhaust:

$$K_e = \frac{1}{2}mv^2$$

This is why fast speeds are so difficult- the amount of energy needed goes up exponentially. Let's look at it from a basic level, assuming 100% efficiency how much energy would you need to accelerate a 150,000 kg payload to 1 kps?

$$K_e = \frac{1}{2}(150,000)1000^2 = 7.5 \times 10^{10} \text{ Joules}$$

If we raise our ships final velocity to 10 kps we can calculate:

$$K_e = \frac{1}{2}(150,000)10000^2 = 7.5 \times 10^{12} \text{ Joules}$$

Or 100x times more energy. Even this power is insignificant to the needs of an interstellar rocket. As we can see from Chapter 1 and further explore throughout this book, the distance between stars is so vast that even a 10kps is far too slow- we would need speeds 10x or even 100x more. The only mitigating factor is that the energy equation does not consider the amount of time that we took to impart this much energy. This is called power. If this 7.5 trillion Joules was imparted to our ship within a minute, the power would be huge.

EQUATION 3-14 $P = \frac{E}{t}$

$$P = \frac{7.5 \times 10^{12}}{60} = 1.25 \times 10^{11} \text{ watts/sec}$$

If we impart this velocity over a day, the results are less (though still jaw dropping) intimidating:

$$P = \frac{7.5 \times 10^{12}}{(24 \times 60 \times 60)} = 8.685 \times 10^7 \text{ watts/sec}$$

Note that in the Energy and Power equations above, the amount of energy we calculated was only to get the payload moving to that final speed therefore these numbers represent the minimum power required. This assumes zero weight for fuel! In reality we will need far more power. If we are propelling our rocket with chemical engines, our rocket initial mass will be 3,000,000 kg – so we will start off as pushing this mass and as we expel our fuel mass, we will gradually work our way down to the 150,000 final weight.

We can quickly see what a challenge power will be to our rocket ship design. To get up to very high speeds required a tremendous amount of energy. Furthermore, and as we will discuss later, generating and handling this amount of energy is a significant engineering challenge. The good news is that this amount of power says nothing about how long it took to gain this much velocity. This is fortunate as the power demand to quickly accelerate a rocket to such a high speed quickly is very challenging. If we spread this energy requirement out over several weeks or months, the instantaneous power required would be more achievable and reasonable. If the power supply is too small you may take decades or even centuries to provide the necessary power to accelerate our vehicle up to speed. A balance will have to be reached in our design- a reasonably sized power supply vs a reasonable acceleration.

Chapter 4- Surviving in Space- History and Economics

History- the Story Until Now

Many books have been written about the history of space travel and exploration- but this is outside the scope of this book. I will only give a very short summary to help put rockets and spacecraft in context.

For centuries rockets were primarily used for military or entertainment purposes. These chemical “solid” powder rocket propellants were very limited in their I_{sp} and did not have the ability to go long distances. Because of their limited performance their speeds were limited, frequently subsonic. The type of performance required to put an object in orbit was far beyond the capabilities of black powder (notwithstanding the fictional Jules Verne book where a large shell with a couple of astronauts is launched to the moon by a canon). Black powder (also called Gunpowder) combines the fuel and oxidizer into a powder. It is a mixture of sulfur, carbon (in the form of charcoal) and potassium nitrate (otherwise known as saltpeter). The sulfur and carbon act as the fuel and the oxidizer is the saltpeter. Gunpowder releases about 3 megajoules per kilogram. Compare this to hydrogen and oxygen combination where one kg of hydrogen, combined with 8kg of air provides 120-142 MJ/kg of power. The hydrogen/oxygen combination works out to 13.3-15.8 MJ/kg or about 5x more energy than Gunpowder.

High performance rockets were not possible until we started using liquid fuels. Liquid fuels were vastly harder to work with- the normal oxidizer was liquid oxygen which had to be stored at very low temperatures to reduce its volume enough to be practical. Combining oxygen and the fuel in rocket chamber where it burned at very high pressures and temperatures presented a major engineering challenge that required both the materials strong enough and tolerant of high temperatures to survive. With this type of engine, high pressure, high flow pumps were required to quickly provide the necessary propellant and oxidizer into the rocket chamber.

Despite some research done by individuals and the government before WW II, as had been the case in prior centuries, it was the military that provided the funding to solve these major design challenges. The penultimate result of this was the German V-2. This program, along with the V-1 is estimated to have cost the equivalent of \$40 billion dollars.

Up until the 1950's the military remained the sponsor of most rocket development- primarily as a means of delivering nuclear bombs quickly and at such a high speeds and altitudes that they could not be intercepted. These rockets, while not able to go into orbit, were fast and powerful enough to go into ballistic trajectories that carried them well into space. One of the results of this perigee is that the original large scale rocket programs focused on one time use- reusability was not required. Even then it was recognized that making a reusable spaceship and engines was as big a leap forward as had been from going from solid to liquid fuel and oxidizer.

Rockets are relatively simple devices except for their engines. As with aircraft, the engines are frequently the single largest cost element and the number one driver of maintenance costs. Engines are the most highly stressed part of either a rocket or airplane, but with airplanes you have the added requirement that the engines are used for thousands of hours and thousands of startups and shut

downs. Furthermore, aircraft engines have to be relatively cheap to maintain and this adds to the upfront design costs. If an aircraft engine was not cheap to maintain (and extremely reliable), the entire airline industry would never have grown into the massive business it is now.

Until now most rocket engines have not had to deal with the challenge of reusability and cheapness. One of the first exceptions to this was the Space Shuttle Main Engine which in the 1970's and 1980's who's engines, both the solid boosters, and main engines, were designed to be reusable. After many years and billions of dollars of development costs, this turned into a marvelous engine with high performance and high reliability. What it did not do was turn out to be cheap- either to build or maintain.

Economics

I wanted to spend a little time discussing the economics of spaceflight.

The Space industry is huge and growing rapidly. In 2018, according to the FAA, the overall global space economy was \$345 billion.

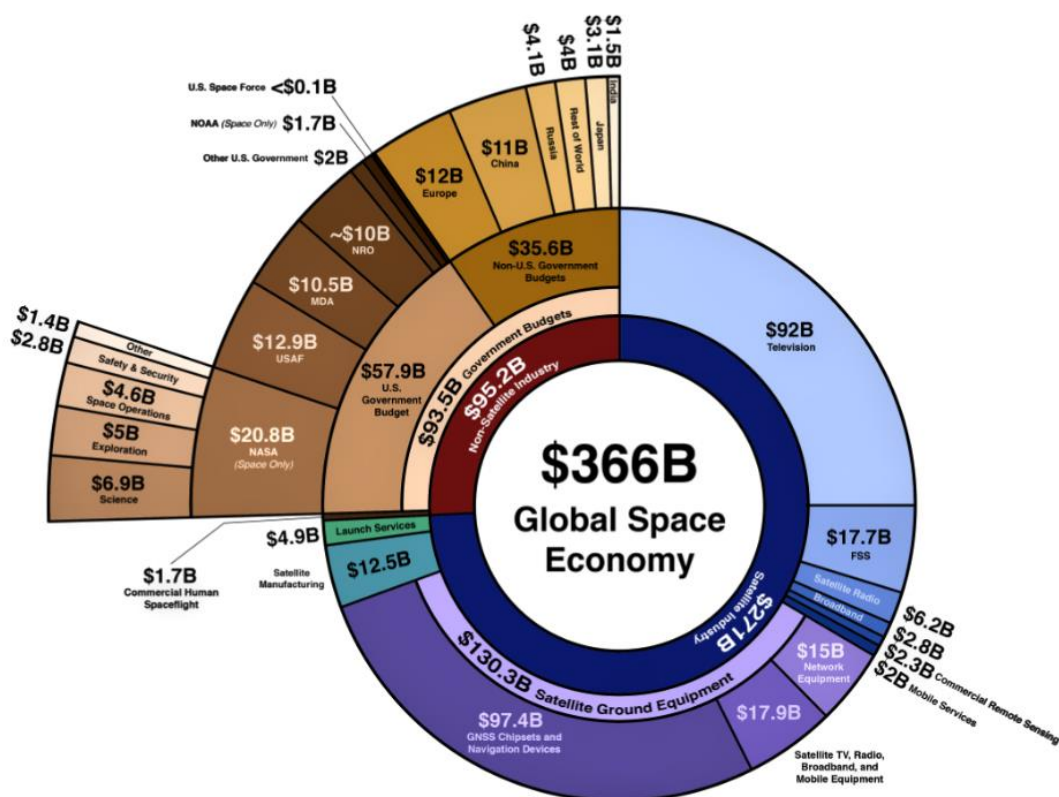


FIGURE 4-1 THE SPACE INDUSTRY-2018 (BRYCE SPACE AND TECHNOLOGY, 2019)

What is interesting in this chart is that the overall cost of launching rockets into space is relatively small- the so-called Launch Services portion is only \$4.9 billion. Why is this? Perhaps counterintuitively one of the major reasons launch services are so small is it's so expensive to launch into space. The high cost of rocket launches means certain industries (tourism, manufacturing) have never, literally, and figuratively taken off! Instead, services- like communications, weather, television, mapping, are the primary source of revenue- once launched they provide a fee-based service that generates healthy revenue stream over many years.

The high cost of launching creates a chicken or egg scenario. The costs are so high that it never creates demand for more launches. Furthermore, low launch cadence means higher cost and lower launch reliability. The best way to improve reliability is to launch frequently and apply lessons learned from any accidents that occur.

Demand for more launches would increase innovation and encourage capital to be invested in new technology, but just as importantly encourage new approaches which would drastically lower the costs of launch and improve reliability. Furthermore, because of the tremendous launch costs, and the resulting low demand for launch services Satellites are overdesigned and very conservative. Up until the first decade of the 21st century, only a few dozen large satellites might be built each year across the entire globe. At these low production rates, there were no economies of scale. You don't want to launch a satellite that costs a billion dollars to make and \$300million to launch and have it fail in the first year. As a result, you use only tried and true technologies. The high costs of launch not only ensure launch costs stay high because of a low cadence, but also ensure the high costs of manufacturing satellites.

Any starship we create will have substantial costs to develop the technologies and to build the spacecraft. Costs can quickly spiral up especially for new or unproven technologies. Regardless, access to space at lower rates is key to any long term colonization and exploration of space.

The good news is that over the last ten years many of the accepted practices in the space industry have changed... it can truly be said that the changes are revolutionary. Lower launch costs are leading to more launches, more satellites, more technological innovations, as well as greater economies of scale. We have seen similar occurrences in many industries- as industries mature costs drop. The most common example of this is the electronics and the way computers, phones and tablets have both dropped down in cost even while vastly improving in capabilities. For many "heavy" industries, costs drop only to a certain point and then level off. This is most common in industries that use a lot of material in the fabrication or where technology can't substantially change the means of production. A car is always going to have a couple of tons of steel, aluminum, and plastic so there will always be a limit on how low its price can go.

Fortunately, the logjam of high prices for launches has changed- primarily because of one disrupter- SpaceX. The Falcon 9 first stage is reusable, and because of the higher launch cadence, considerable economies of scale have occurred. Furthermore, and not coincidentally, SpaceX is looking to mass produce satellites- satellites that will be 1/100th the cost of a typical satellite. Their Starlink system already has many thousands of satellites mass produced at relatively low prices- reportedly as low as \$250,000 per satellite (Wang, 2019).

One reason I have tried to keep the technology conservative in this book is that the costs as well as schedule are easier to predict if there are no technological unknowns. Building a fusion rocket has never

been done... indeed after many billions of dollars and nearly a century on research and development and the building ever more elaborate engineering test articles a working practical fusion plant has remained elusive. For this reason, I did not consider fusion to be a viable technology for our starship in this century- though it certainly holds the potential to be a game changer in the future both for power generation and propulsion.

In a similar but slightly different vain, I prefer not to count on huge engineering works in space- even if the science and engineering behind them are well known. Even though from a technology point of view, there are minimal risks, the engineering and industrial challenges are so large that to build these structures would be dauntingly expensive or take decades or even centuries to accomplish. As we shall see, any interstellar spacecraft we build will need a space infrastructure that currently does not exist. Large-scale spacecraft cannot rely on all the equipment and supplies coming from the earth. A large portion of the raw materials and manufacturing capabilities will have to be sourced from space. As discussed in later chapters, some of the requirements that are needed to support interstellar rockets are truly large. As an example, we can construct huge microwave or laser facilities to beam Gigawatts to propel a solar sail. However, we have never built lasers anywhere near this large- even though there is nothing that would prohibit us from doing so (other than the expense involved). In addition, the aperture of these lasers, required to focus this power billions of kilometers onto the solar sail, are dozens if not hundreds of kilometers in diameter. In this case (as opposed to fusion) engineering is well known and there is no need for a scientific or engineering breakthrough, but the size of the project is far larger than has ever been considered or built before. When possible, I have tried to keep the engineering projects small, but when it comes to interstellar starships the need for large infrastructure is unavoidable.

Finally, in some chapters I develop cost estimates for various starship configurations. In many cases these are real WAGS (Wild Ass Guesses). In general, these cost estimates are very low compared to traditional government contracts. That is because I assume we are not using the government to actually build our Starship with a Cost-Plus contract. In the next section we will see how SpaceX has not only developed its own engines and rocket for a fraction of a traditional government contractor (up to 10x cheaper) but have reduced actual launch service costs by 75% to 90%. I assume that, except for some very basic research, the launch and construction of these starships are more in line with a service contract, similar to the lunar lander contract of \$2.89 billion that was awarded to SpaceX.

Launch Costs

There are many companies and governments that have developed space launching capabilities, however, until recently, they developed rockets with the funding and support of the government. There was little incentive for the companies to innovate since the markets were dominated by a few governments or government sponsored entities. As a result, as with many industries throughout the world, government sponsorship led to overall stagnation, tremendous inefficiencies (high costs), and no real reliability or performance improvements. In this scenario, corporations essentially became extensions of the government with organizations that mirrored and adopted both the positive and negative aspects of such an arrangement. Traditional government contractors provided high job security

and good pay but have substantial disadvantages in competitive environments because of the lack of innovation, lack of motivation, limited incentive to improve efficiency, extensive bureaucracies, and conservative decision-making cultures. It is a fact that many of the rockets launched by these government sponsored industries in the early 21st century are using rocket designs that date back to the 1950's. Despite vast sums spent on each launch, and many billions more spent throughout the decades to "improve" rockets, the only effect has been slightly higher launch reliability than in the 1970's (1% vs 2% failure rate) and inflation adjusted prices that essentially remained unchanged. It is a symptom of this stagnation that one of the most common US launch vehicles in the early 21st century did not even rely on an American made engines but relied on those manufactured in Russia!

These facts should raise many eyebrows for people that believe governments can drive meaningful engineering and industrial progress. During crises and national emergencies governments can push development and improvement (witness the armaments industry during WW2 and the Apollo program).

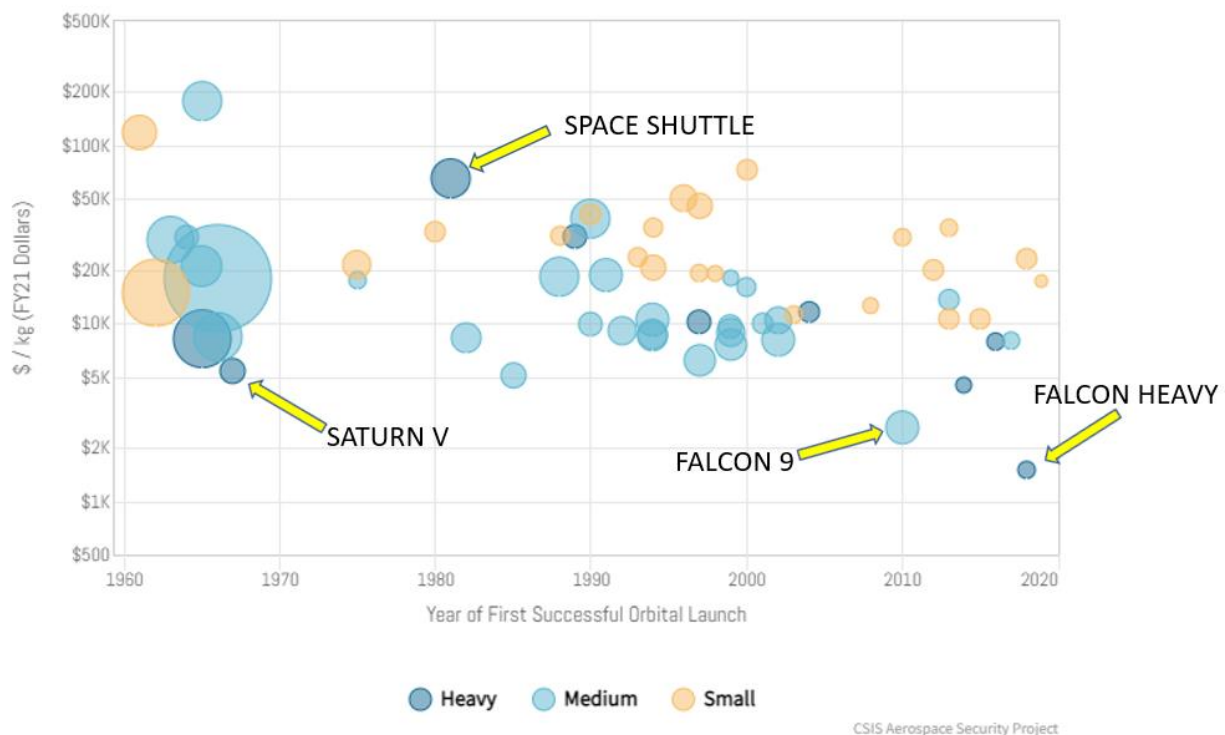


FIGURE 4-2 SPACE LAUNCH COSTS- ANNOTATED WITH SELECTED LAUNCHERS (ROBERTS, 2019)

They can also sponsor technological developments in risky areas that have little short-term payoffs. However, once the urgency is gone the vision or goal dissipates, the political will evaporates, and the programs become employment programs to win votes or to conduct social engineering. If we need to colonize space, no government is likely to take the lead- but rather the opposite- government sponsorship would probably be a death nelly for any hopes of colonizing our own solar system and certainly other star systems.

This discussion on space markets and the future of space exploration is important so as to understand its impact on the eventual attempt to colonize the stars, or even planets in our solar system. Until SpaceX it was natural to assume that governments would take the lead on colonizing. Now, it appears

that private industry will. The US government has talked about returning to the moon and eventually Mars for the last 50 years and has essentially made no progress.

Over the last few years, this situation has started to change. In the early 2000's two new players arrived on the scene that promised to shake things up- Blue Origin and SpaceX. Both started within a couple of years of each other. Over the last two decades, it does not appear as if Blue Origin has produced much on its own and has, more recently and more worryingly, attempted to get government money to help with its design work. SpaceX, while also occasionally accepting government money for development work has on the whole, gets its revenue by actually providing a service- the launching of payloads or developing the Starlink satellite network. They mostly self-funded the partly reusable Falcon 9 which, depending on the mission needs, and is able to launch at fraction of historical prices (see Figure 4-2). Note that the nominally reusable Space Shuttle was one of the most expensive launchers in history... far more than even the Saturn V. Without SpaceX the price of launches stayed relatively consistent over the last 60 years.

Rocket Science is hard, and despite the tremendous success of SpaceX, the Falcon 9 has proven the exception to the rule that most of the space industry had become a job employment program for politicians to get votes. SpaceX is the only large space launch provider that generates a majority of its revenue by providing services. SpaceX has been an outsider that was never a part of the traditional military industrial complex. Nevertheless, since it was founded it has taken over the majority of US launches. Just as importantly, the revolution begun by SpaceX is trickling throughout the industry and changes can be seen- albeit slowly. It is no longer business as usual.

The historical American launch provider, United Launch Alliance, counted on historical rocket designs, most dating back to the 1950's, to generate their revenue. In response to SpaceX, they have substantially streamlined their operations over the last five years. Unfortunately, as with Blue Origin, they have failed to develop a new, revenue generating rocket (despite billions of private and public money). Hopefully this will change over the next few years and both ULA and Blue Origins will finally be able to deliver on their respective Vulcan and New Glenn rockets. Until then, Space X, which already accounts for most annual US launches (upwards of 75% in 2022, and 90% in 2023) will continue to dominate the launch industry. Starting in 2022 SpaceX put more payload mass into orbit than the rest of the world combined!

The Falcon 9 development is a case study of the inefficiencies of government and traditional contractors. A NASA study originally estimated that developing the Falcon 9 as a NASA program would have cost the taxpayer about \$4 billion, or about twice that which Space X spent. An updated analysis which factored in the lessons learned from Falcon 1 led to a revised number of \$1.695 billion for the NASA way of doing business vs about \$443 million for Space X, so even a larger percentage discrepancy (NASA Associate Deputy Administrator for Policy, 2011). When looking at the Space Launch System (SLS for short) which NASA is currently developing these reports may be too generous with regards to NASA's efficiencies. The SLS, while much bigger than Falcon 9, is a throwaway rocket and in many ways is less advanced. This behemoth has so far vacuumed up nearly \$18 billion of taxpayer money and its first launch occurred in early 2023- many years late. It will also cost an estimated \$1.8billion per launch! As mentioned, and in defense of NASA, much of this cost is driven by the desire by politicians to steer money to their constituents, hence the alternate name critics created for the SLS- the Senate Launch

System. This shows that absent national urgency, NASA will serve, as best, a facilitator of any future space colonization, and not the lead.

There are other misconceptions about the space industry and space policy that have proven quite detrimental to the colonization of space and the building of a space-based economy. Occasionally we may hear of the need to have multinational efforts to colonize space or to embark on colonizing planets. The justification for this is frequently that the required resources (i.e., money) are too large for any one nation to go it alone. The reality is that most of these statements seem to come from public relations spokespersons, the media or people that have no idea of how economies work. The tremendously expensive International Space Station is one example of this absurd premise. To date it is estimated that \$200 billion has been spent. While it is truly a technological wonder, can anyone with a straight face really say it was worth \$200 billion? Working with dozens of countries had the opposite effect and did not streamline or make the final product cheaper. Coordinating design and manufacturing between different countries with different languages and cultures frequently adds years to the construction.

Furthermore, even though our minds boggle at its \$200 billion price tag, in the grand scheme of things, this is only half of the \$400 billion of the F-35 fighter program spent through 2021. Even this number is less than 1/10th of the worth of Apple Inc. Spending ten billion a year on a program is not impossible for large governments or even some of the largest companies.

The fact is that space is a hard and challenging environment and not for the faint hearted. It should be available for those who have a passion for it- and not a justification for a large bureaucracy with political and social motives. If our goal is to colonize space (as with Musk's goal for Mars) then the reward is the achievement of the vision and not job security. If it becomes a government program, it will be subject to the whims of politicians and national strategy that will distort its true mission and eventually lead to a job's program with little actual progress.

The key point to be made is that launching from earth is expensive, but it is expensive because of the slow launch cadence and government involvement. It is likely to get cheaper over the next few decades as new reusable launchers come online, but its not likely to ever get cheap. Throughout this book we will assume a robust launch industry where costs are brought down to \$500/kg. I am not convinced it will ever go much below this- we have seen how for each kilogram put into space we will always need ten to twenty times more fuel. What this means is that, except for the smallest programs, larger starships will need to source most of their raw materials from space.

Resource Availability

When describing the Solar System and beyond in Chapter 1, we spoke a bit about the available resources in the universe. Historically all resources used by humans on our spacecraft (fuel, spacecraft, food, oxygen, and water) have come from the earth- with the sole exception of using Solar Power on some spacecraft. This is not sustainable or efficient in the long term. As seen, for every kg of cargo placed in orbit or sent into deep space, ten or twenty times more fuel is used to get to space. For larger

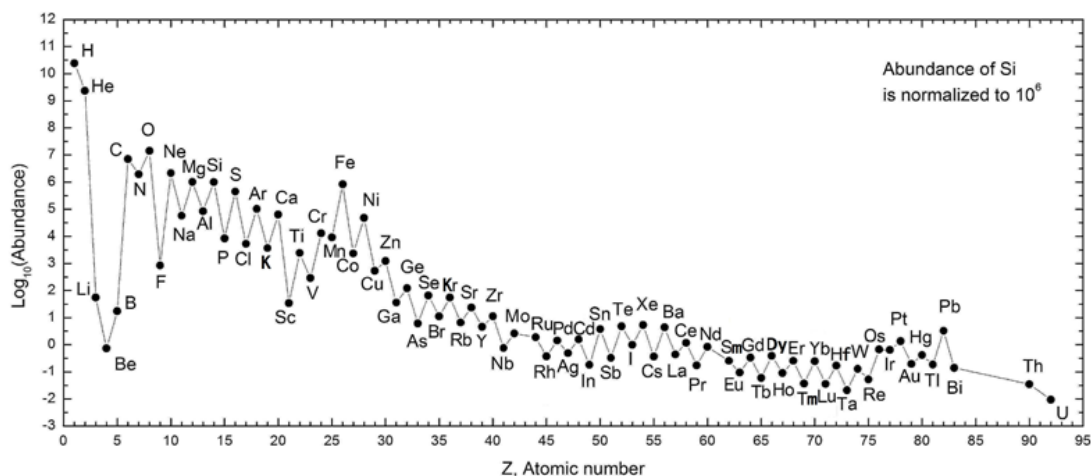


FIGURE 4-3 SOLAR NEBULA ABUNDANCE PLOTTED ATOMIC NUMBER VS ABUNDANCE LOG SCALE (LODDERS, 2007)

missions, larger spacecraft, or for more massive colonies we need to start using the resources that are available “out there”. The Nebula that formed our solar system had all the components that we need to establish a huge space-based economy (see Figure 4-3).

Most of this primordial material is still in the solar system, but not evenly distributed. The sun contains some 99.86% (Woolfson, 2000) of this material and is essentially inaccessible. Per the original composition of the solar nebula, it is primarily hydrogen... though as the sun ages more and more of the hydrogen that is locked up in the sun will be converted to helium.

The next large repository of material are the planets. Jupiter has about .1% (or 1/1000th) of the sun's mass, but about 71% of the remaining mass of all the other objects in the solar system. Jupiter is

approximately 318x more massive than the earth. Jupiter and Saturn together have 92% of the mass of

CHAPTER 2. MATTER AND ITS ATOMIC STRUCTURE

Table 2.2: Most abundant chemical elements in the solar nebula

Atomic number <i>Z</i>	Name	Chemical symbol	Atomic weight (¹² C=12)	Melting point at 1 atm (K)	Boiling Point at 1 atm (K)	Abundance (atoms per 10 ³ Si atoms)	
						solar atmosphere	CI chondrites
1	Hydrogen	H	1.01	14.0	20.3	28 200 000	5 600
2	Helium	He	4.00	—	4.2	2 400 000	—
8	Oxygen	O	16.00	54.8	90.2	19 000	7 700
6	Carbon	C	12.01	3 820	?	9 330	810
10	Neon	Ne	20.18	24.5	27.1	3 390	—
7	Nitrogen	N	14.01	63.3	77.4	2 340	40
12	Magnesium	Mg	24.31	922	1 363	1 070	1 050
14	Silicon	Si	28.09	1 683	2 628	(1 000)	(1 000)
26	Iron	Fe	55.85	1 808	3 023	890	870
16	Sulphur	S	32.06	390	718	600	435
13	Aluminum	Al	26.98	934	2 740	83	85
18	Argon	Ar	39.95	84.0	87.5	71	—
20	Calcium	Ca	40.08	1 112	1 757	65	62
11	Sodium	Na	22.99	371	1 156	60	58
28	Nickel	Ni	58.69	1 726	3 005	50	49
24	Chromium	Cr	52.00	2 130	2 945	13.2	13.5
17	Chlorine	Cl	35.45	172	239	8.9	5.3
15	Phosphorus	P	30.97	317	553	7.9	10
25	Manganese	Mn	54.94	1 517	2 235	6.9	9.3
19	Potassium	K	39.10	336	1 033	3.7	3.8
22	Titanium	Ti	47.88	1 933	3 560	3.0	2.4
27	Cobalt	Co	58.93	1 768	3 143	2.2	2.2
30	Zinc	Zn	65.38	693	1 180	1.1	1.3
9	Fluorine	F	19.00	53.5	85.0	1.0	0.85
29	Copper	Cu	63.55	1 357	2 840	0.46	0.54
23	Vanadium	V	50.94	2 163	3 653	0.28	0.29

Sources: N. Grevesse & A. J. Sauval 1998, Space Sci. Rev., 85, 161; *CRC Handbook of Chemistry and Physics*, 1986–87 Ed. (Boca Raton, Fla: CRC Press, Inc.), B-5.

Table 4-1 (Grevesse & Sauval, 1986-1987)

all the planets... and like the original solar nebula and our sun, are primarily composed of Hydrogen and Helium.

The “terrestrial” planets, Mercury, Venus, Earth, and Mars are rocky planets and are all more massive (though not necessarily larger in size) than any of the moons. The earth itself is almost 9x more massive than all the moons in the solar system combined and is about 81x more massive than our own moon. The moon itself is about 25x more massive than all the asteroids combined. As opposed to the gas and ice giants, these planets, being much less massive and closer to the sun, are depleted in the most volatile elements which would have been carried off early in the evolution of the solar system by the radiation pressure and solar wind of the sun.

The asteroid belt located between Mars and Jupiter is home to hundreds of thousands of small, irregular shaped bodies. Despite its relatively small mass, the asteroid belt is relatively close and therefore easy to get to. Their low gravity and close location to the sun also mean that they are usually low in volatiles- though some do apparently have substantial quantities of water.

The Kuiper belt on the other hand is much more massive than the asteroid belt- though because it is so distant many Kuiper belt objects have not yet been discovered. In totality, the Kuiper belt is suspected to have a mass up to 10x greater than our moon. (Delsanti, 2006) As opposed to the rocky and metallic asteroids, objects in the Kuiper belt are primordial and represent more closely the original makeup of the solar system, except for the hydrogen or helium which are too light to be kept by small bodies. The Kuiper belt objects will have large amounts of frozen volatiles including water (tying up the hydrogen) and others like ammonia (nitrogen and hydrogen) and methane (carbon and hydrogen). It is believed that most of the comets that are observed come from the Kuiper belt.

Further out is the Oort cloud with what are believed to be trillions of objects larger than 1km with a perhaps five times the mass of the earth- and perhaps much larger (Morbidelli, 2005) (Weissman, 1983). Like the Kuiper belt, objects in the Oort cloud are much closer in composition to the original solar nebula and Oort cloud objects are made of a large proportion of volatiles.

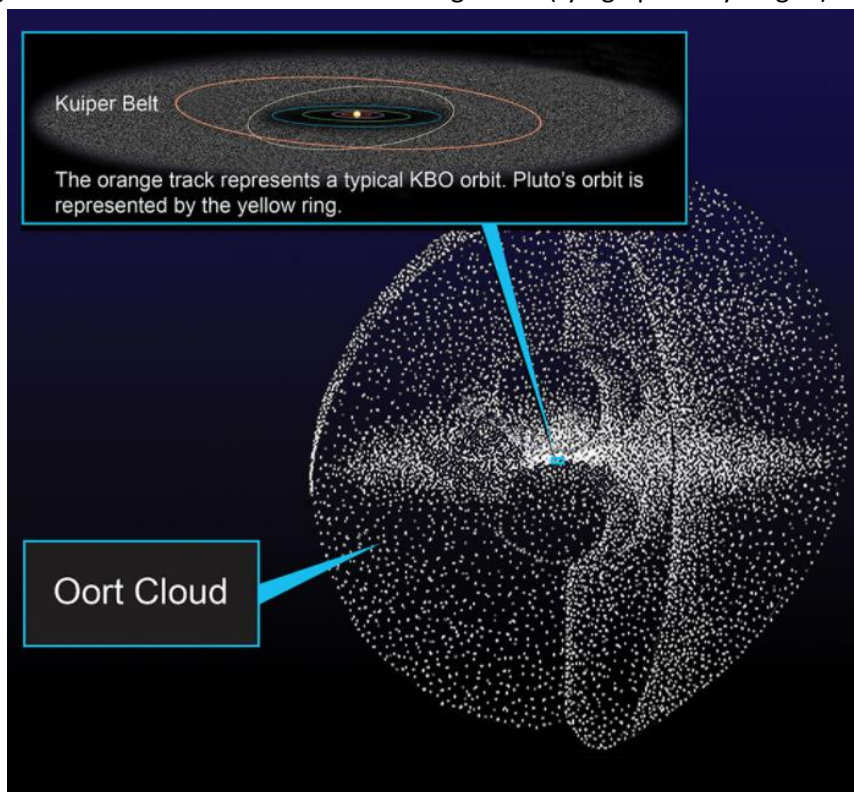


FIGURE 4-4 THE SOLAR SYSTEM- KUIPER BELT AND OORT CLOUD (YEOMAN, N.D.)

The end result of this is that there are vast amounts of material that are technologically accessible in the various rocky planets,

moons, asteroids, Kuiper and Oort cloud objects. Because of the distance of the Kuiper and in particular the Oort cloud, reaching them can be very difficult... in some cases it may take centuries.

There have been many studies, and space probes that have tried to identify the resources that are available from various bodies within our solar system. Starting with the moon, scientists have been able to determine the approximate quantities of many elements, however there are still many unknowns and additional exploration is required. Because of their close proximity, asteroids have been the subject of considerable scientific interest. Several missions have either been done (Dawn), or are in progress (Lucy, Psyche) to help us better determine the composition of the asteroids.

Lunar surface chemical composition^[1]

Compound	Formula	Composition	
		Maria	Highlands
silica	SiO ₂	45.4%	45.5%
alumina	Al ₂ O ₃	14.9%	24.0%
lime	CaO	11.8%	15.9%
iron(II) oxide	FeO	14.1%	5.9%
magnesia	MgO	9.2%	7.5%
titanium dioxide	TiO ₂	3.9%	0.6%
sodium oxide	Na ₂ O	0.6%	0.6%
		99.9%	100.0%

**TABLE 4-2 LUNAR SURFACE CHEMICAL COMPOSITION
(TAYLOR S. R., 1975)**

The Apollo Astronauts did some preliminary exploration of the moon. The surface of the moon's chemical composition varies substantially depending on where the samples were taken (Table 4-2). We can quickly see that Silicon, Aluminum, Calcium, Oxygen, Iron, Magnesium, Sodium and Titanium are very abundant. Volatiles such as hydrogen, Nitrogen, Xenon, and Argon are very rare. Carbon is also very rare- at a measured quantity of 82ppm and only in the top meter or two of the surfaces. The carbon has been deposited there from eons of being blasted by the solar winds and it is not believed that the moon naturally possesses much if any carbon. Any long-term voyage will require carbon, along with various other nutrients for plants and other life that the moon lacks- elements such as potassium and phosphorus. These elements are present in Chondrites which are meteorites that came from non-metallic asteroids (Figure 4-5).

Asteroids, Kuiper Belt and Oort Cloud objects have different proportions of materials. Asteroids would be relatively good for metals, but relatively poor for water, and even worse for volatiles. Objects in the Kuiper belt and Oort cloud would be the opposite- rich in volatiles but poor in metals.

Asteroids originated in a vastly different part of the solar system and evolved in a different manner than the moon. Their makeup is still poorly understood, as opposed to the moon where samples were obtained. Asteroids are classified based on earth based spectral measurements which help determine

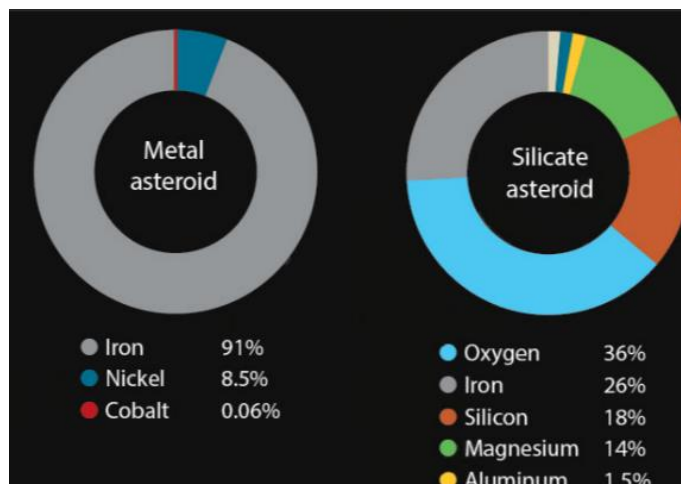


FIGURE 4-5 M-TYPE AND S-TYPE COMPOSITION (COURTESY NASA)

their composition. There are various ways of categorizing asteroids. The most commonly used place most asteroids into one of three categories: M, S and C type.

C-type: Carbonaceous represents about 75% of known asteroids. They exist mostly at the outer edge of the asteroid belt at about 3.5AU from the sun. It is thought they are composed of clay and silicate rocks (rocks consisting of molecules of silicon and oxygen). They contain a high percentage of carbon, phosphorus and water containing materials. There are many different subclasses of C-Type asteroids. For instance, CI Chondrites have substantial amounts of

virtually all important elements except for some volatiles. They have been observed to consist of up to 22% water (Norton, 2002, pp. 121-124). Chief shortages are Helium, Neon, Nitrogen, and Argon. Fortunately, except for Nitrogen, the other materials are not very important to either human survival or industrial purposes.

S-type: Silicate (or stony) asteroids are the second most common type of asteroid at about 17%, and contain more metals, including Nickel and cobalt as well as rarer metals than the C-type, but they mostly contain magnesium and silicates.

M-type: Metal asteroids are rare (about 7% of all asteroids) and are made of mainly iron, nickel and cobalt.

In addition to these three types there are other less common types of Asteroids that have abundant water. Indeed, some of the more distant asteroids are believed to be comets and are mostly water or volatiles. Even with the distant asteroids and comets, gaseous and liquid Nitrogen remains rare, as its boiling point is much lower than water and except for the furthest reaches of the solar system, heat from the sun would cause it to boil off and be driven out of the solar system. However, Nitrogen may be found combined with Hydrogen where it makes ammonia. Ammonia can be found on comets, and Kuiper or Oort Cloud objects. In addition, there are some substantial Nitrogen reservoirs scattered in other places- for example, even though Nitrogen makes up less than 2% of the atmosphere of Venus, its atmosphere has more nitrogen than the earth's. This is because Venus's atmosphere is much more massive than that of the earth. In addition, on some of the larger moons like Titan (but also Triton the Moon of Neptune, as well as the minor planet Pluto) there are very large reservoirs of Nitrogen.

Some other materials appear quite rare in the solar system but are essential for life. Examples are potassium and sodium. Fortunately, even for long term manned missions, the amount of Potassium and Sodium required are not particularly large.

Despite the vast resources available the fact is that there is no mining industry and no experience with extracting resources from space. For a "small" starship, such as what we will describe in chapters 5-10,

all resources can be launched from earth. When we get to large “world ships” a vast majority of the ships raw materials will have to come from space. We will discuss this more thoroughly in later chapters.

Making Space Habitable

Space is deadly to life but, in many ways, more manageable than on earth because it is relatively unchanging. If you put a spacecraft in orbit a certain distance from the sun and point one end of the spacecraft at the sun, the sun facing side will get brutally hot until it reaches equilibrium. Conversely an object in shadow will always drop down to near absolute zero. Space is pretty much always a vacuum, and the solar thermal radiation remains predictable, though cosmic radiation can vary depending on the sun’s flare activity as well as distant astronomical events.

Despite being relatively unchanging the fact is that deep space lacks everything a person needs to survive:

- Easily available resources including Air, Water and food
- Energy. Away from a star deep space is tremendously cold- near absolute zero
- Gravity, depending on your location. Gravity may be present but in most cases your spacecraft is in orbit and thus in what is called “freefall”.

About the only thing in deep space are the faint photons coming from the stars as well as blasts of cosmic radiation which frequently come from supernova, neutron stars or black holes. Nearer to the sun or another star you may also get a tenuous wind of solar radiation in the form of charged particles.

Starting with the most basic requirements, an astronaut needs to be protected from the vacuum of space by a bubble of pressurized air. Without this bubble of air, he would pass out within about 15 seconds and die of oxygen deprivation withing a couple of minutes. Just providing air to the lungs is not enough- his whole body needs to be pressurized- otherwise he will not be able to suck in or expel the oxygen in his lungs. Indeed, trying to force oxygen to the lungs without the atmospheric pressure around his body could cause his lungs to burst. Furthermore, if a person quickly goes from an environment at atmospheric pressure to a vacuum the nitrogen in his blood will boil (the same issue that occurs when deep sea divers ascend to the surface to quickly) from the bends so it is merciful that that they will die swiftly.

After providing his or her bubble of air, the astronaut needs to be protected from the bitter cold of space when in shadows, as well as some protection from the brutal solar radiation if in sunlight. As opposed to what happens in the movies, the extreme temperatures the astronaut would be exposed to would not kill them quickly... as long as their organs were provided with blood and oxygen, they could survive many minutes. Despite the intense radiation and bitter cold, the skin is an effective protection against the vacuum of space. Keep in mind that the only way to cool off when you are in a vacuum is radiative heat, which is a lot less effective than conductive heat. So even though space is only a few degrees from absolute zero, it is a vacuum and there are no molecules to carry the heat away. This will be important later when we discuss spacecraft power supplies and the need to get rid of excess heat- it is surprisingly hard to get rid of heat in space. Similarly, the unprotected skin would be damaged by the

unfiltered radiation from the sun but again, a few minutes would not destroy it- though it would quickly become uncomfortable.

The third most critical requirement is water, without which the astronaut would expire within a few days.

The fourth big requirement is food or nutrition. To survive for weeks or months the astronaut would need both calories in the form of sugars, but also vitamins and minerals.

A fifth requirement is power. It may seem obvious but to be able to keep our astronaut warm, or cool him or her down, to provide light to function in, power is needed. Throughout this book we will look at various sources of power. As with water, a few days without power and the space station or spacecraft would become uninhabitable.

The sixth requirement is protection from radiation- specifically charged particles (cosmic rays). In deep space, away from the protective magnetic field of earth, cosmic rays from the sun and from deep space will constantly be sleeting down unto our unprotected astronauts. Within a couple of days, it is easy to receive what is regarded as the annual safe limit of radiation on earth. Within a year or two, damage to DNA could become severe leading to a much higher chance of cancer and damage to the reproductive organs. A few more years of exposure to radiation in space will lead to an increasing mortality rate.

The seventh requirement is gravity. Gravity is not needed for unmanned probes but is required for humans. Without gravity our bones lose calcium and become gradually brittle. There are additional physical effects that occur without gravity, but data is still being collected. Regardless, enough scientific studies have occurred to say that a few years without gravity would have serious health consequences.

The eighth risk, a rather small one that still needs to be addressed, is meteor protection. The earth is protected by its thick atmosphere from small meteors and larger meteors are extremely rare. In space there is no protection from even the smallest meteors. Although statistically a low-risk area, any long voyage spaceship must consider the possibility of a meteor strike.

We will look at all these requirements throughout this book. All spacecraft over the last 50 years have different means of addressing the first five items. However, as we have never sent out large crews on multiyear missions, the two biggest remaining challenges are the requirements for gravity and cosmic radiation protection. Neither have really been seriously addressed but the engineering requirements are well known. Finally, we will also briefly discuss the need for meteoroid protection.

Artificial Gravity

In over 60 years of manned space exploration, one thing that astronauts have never had is gravity. Gravity is something that is both needed for the long-term health of astronauts, as well as making many everyday tasks such as eating and going to the bathroom, much easier. However creating gravity requires very large spacecraft.

It has been known for centuries how to produce an artificial gravity that is virtually indistinguishable from the gravity on earth. It takes advantage of the principle of centripetal force. If an object is given a push it will move, in the absence of friction or gravity, in a straight line. If the object is confined by the floors of a rotating cylinder, they will constantly be pushed upwards, simulating gravity.

The artificial gravitational acceleration is defined by the formula:

EQUATION 4-1 $a = \frac{v^2}{r}$

Einstein's General Theory of relativity made the rather startling statement that the gravitational force you feel from a planet's gravity is identical to that you would feel if you were in an accelerating frame. Reduced to its simplest, this statement means that Gravity is not a force but can be simulated. In theory all you need is to spin a spacecraft

quickly around a central point and its inhabitants would feel gravity. The problem with artificial gravity is that, while a point like (or very small) object, artificial gravity and a planetary gravitational field would feel the same, in reality artificial gravity and a planetary gravitational field do have differences when you are dealing with larger objects and objects in motion.

To achieve an earth normal 1 g acceleration requires either a quickly spinning station of a small diameter or a slowly spinning station of large diameter. Building a small, rapidly spinning station would be easiest, but will cause several problems for its inhabitants.

- Gravity will vary significantly as you travel towards or away from the axis. Your foot will feel more gravity than your head. Just standing up or sitting down will cause gravity to vary noticeably.
- If you were to walk or run inside a spinning cylinder along the axis of spin it will cause you to feel a higher gravity. Conversely traveling opposite of the spin will cause the apparent gravity to decrease. For instance, let us say that the outside of cylinder is moving at 15kph. If you ran opposite this spin at 15kph your gravity would seem to have no gravity (though you would fly face first into the floor). Conversely if you ran in the same direction as the cylinder was spinning, your weight would quadruple (in keeping with the v^2 in equations 4-1).
- Related to these, changing the distance from the axis imparts a Coriolis effect. This effects the inner ear and can quickly lead to motion sickness.

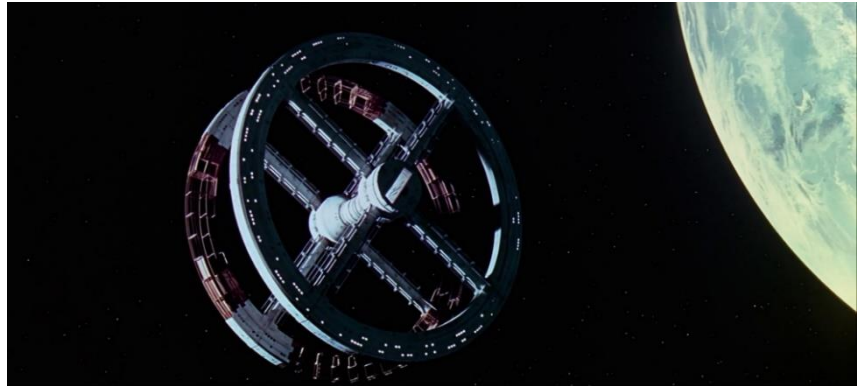


FIGURE 4-6- A CLASSIC ROTATING SPACE STATION FROM 2001: A SPACE ODYSSEY



FIGURE 4-7 THE CURVED FLOOR FROM THE MOVIE 2001: A SPACE ODYSSEY. NOTE THAT THIS SPACE STATION HULL APPEARS TO BE ABOUT 6 METERS WIDE

These problems can be fixed. On earth, humans do not feel the Coriolis effect or the differences in gravity from head to foot because even though the earth spins rather rapidly, it is so huge compared to us and its rate of spin so low that gravity variations are too small to notice. Compared to the centripetal force, the earth's gravitational field is vastly stronger and uniform- the earth takes 24 hours to complete

RPM	Radius meters	Diameter Kilometers
.1	89426	179 km
.5	3577	7.1 km
1	894	1.8 km
2	223	.4 km
4	55	.011 km

TABLE 4-3 RPM VS DIAMETER FOR 1G

a single spin, and the centripetal effect is far less than the earth's natural gravity. For the centripetal effect to negate the effect of the earth gravity at the equator, the earth would have to spin at the same rate as its orbital velocity- or approximately one revolution per hour.

You can reduce these problems if you make the space spaceship (or space station) very large which will allow you to slow down its rotation rate while still providing the same artificial gravity. The need for a large diameter station, along with the complexities of having a spinning spacecraft, are the reasons we have not built any spacecraft with artificial gravity.

First thing we need to decide is how slow do we need to spin in order not to feel excessive discomfort? Studies done to determine what an acceptable spin rate is vary widely (Hall, 1997). These studies conclusions indicate acceptable ranges for comfort of anywhere from .1 RPM to 6 RPM. Regardless, all tend to emphasis that the larger diameter, slower rotating configurations are better.

Table 4-3 gives some examples of the required diameter for different rotation rates to get one g. Figure 4-8 shows the diameters vs Rotation rates for three different g forces. The large diameter, slowly rotating stations provide the following advantages:

- A larger diameter station will even out the gravity force difference from heads to toe
- A larger diameter will reduce the gravitational changes when moving along the station direction of rotation (i.e. if you are running in the direction of travel your gravity will increase, conversely running opposite to the travel your gravity will decrease).
- Reduce discomfort caused by the Coriolis effects.
- Reduce the curvature of the floors and walls which makes rooms an odd shape an furniture placement difficult.

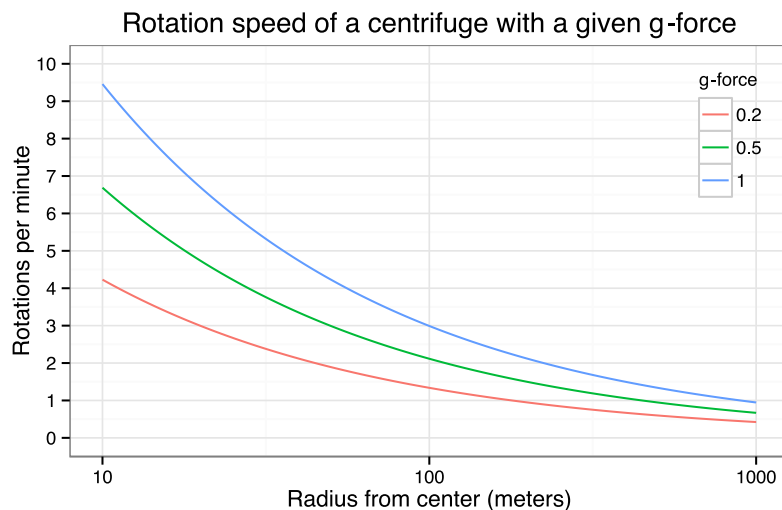


FIGURE 4-8 ROTATIONS PER MINUTE VS RADIUS FOR DIFFERENT G FORCES

- Ease some manufacturing process. All “flat plates” that are formed from pouring (anything from glass, ceramics, steel and aluminum to silicon chips) will have a more pronounced curve for a smaller diameter ship.

In later chapters we will look at the need for artificial gravity and attempt to balance comfort while attempting to minimize the starship size.

Meteoroids

It may be surprising to learn that, unless we are very unlucky, Meteoroids are not likely to be much of a problem for interstellar spacecraft. There are several reasons for this. As discussed, the universe is empty- most material in our Galaxy resides in the stars and planets... very little remains floating in space.

Within our solar system it is much more crowded than interstellar space. But even here, the chance of hitting something even as large as a marble, is quite small. Like the universe, the solar system is very old and most of the original raw material has been swept up to form the sun, planets or, through interactions with these planets (primarily Jupiter) ejected out of the solar system altogether.

At the current age of our universe, very little material remains between stars and even then, it is thinned out over vast distances. There are larger bodies- comet like objects or even planet sized objects free floating between the stars that were ejected from their homes ages ago but even though there are billions of such planets wandering the space between the stars, along with countless smaller objects, space is so vast that the chance of hitting one is quite remote. Nonetheless, the consequences of hitting an object at high speed could be catastrophic and during a voyage that may last centuries, can't be ruled out. Keeping in mind that our Starship will likely be traveling at several hundred kps, impacting even a marble sized object can be devastating. To give an example, a typical glass marble weigh about 5grams. If one hit our Starship was traveling at 500 kps it would release:

KE- $\frac{1}{2} (.005)500,000^2 = 625\text{million joules or } 625,000\text{kJ}$

Converting this to TNT equivalent, one gram of TNT releases 4.184kj. Therefore, a marble sized rock would impart about 149,378 grams of TNT- or 149kg or explosives- more than enough to destroy any but the largest starships if it were to hit in a sensitive area.

The good news is that the size of objects we encounter generally follow the power laws. As an example, compared to a marble, a 1 kg object mass's 200 x more than our marble and would therefore be 200^2 rarer- or 40,000 times less likely.

Throughout any voyage in space, we will be continuously hit by very small dust like particles and less frequently grains or even larger items. Because of this some shielding will be prudent. Since the spacecraft is only traveling in one direction the probability of impact would be primarily in the front so any proposed shielding would be positioned there. Fortunately, our Cosmic Ray shielding (see below) can do double duty and serve as a meteoroid shield. In addition, there is a relatively simple technology called a Whipple Shield to minimize the risk from meteoroids, and this will be addressed in Chapter 15.

Cosmic Radiation

Cosmic Radiation is possibly the most difficult challenge to living safely in space since all the solutions are bulky. As we shall see, a thin steel or aluminum shell is all that is needed to keep the atmosphere inside a ship but this will do little to protect the occupants from Cosmic Radiation. Let us begin our discussion by identifying what is cosmic radiation?

Cosmic Radiation are high energy subatomic particles, mostly protons, atomic nuclei, and electrons, traveling at near light (or relativistic) speeds. They originate both from the sun as well as from outside our solar system- from our own and even other galaxies. Solar cosmic rays are usually relatively low energy protons or atomic nuclei. Much more powerful are the ones from outside the solar system- called Galactic Cosmic Radiation (GCR). One unfortunate reality is that even though the sun is a source of cosmic radiation, the solar wind also protects the solar system from some of galactic cosmic rays. A starship in deep space will not have this protection.

About 90% of cosmic rays are protons (hydrogen nuclei) and 9% are alpha particles (helium nuclei). About 1% are electrons, and 1% are nuclei heavier than an alpha particle. A significant portion of cosmic rays originate from supernova explosions- the explosion that is caused when a large star runs out of fuel and undergoes its final collapse which triggers a massive explosion. Other cosmic rays originate from so called active galactic nuclei. Cosmic rays vary in strength with the weaker cosmic rays far more plentiful and the very strong ones very rare. The highest energy cosmic rays can have as much as 40 million times the energy of particles that are accelerated in the Large Hadron Collider- currently the largest and most powerful particle accelerator built.

When a cosmic ray enters the earth's atmosphere, it can hit nitrogen or oxygen in the upper atmosphere, creating a shower of secondary particles that can reach the earth's surface. Cosmic rays are extremely harmful because either they, or the secondary particles they create, are traveling at tremendous speeds and can pass through a human body relatively easily, leaving in their wake a path of damaged cells. Cosmic rays can also damage electronics. On earth, even with its magnetic field and thick atmosphere, cosmic rays account for about 13% of the background radiation. At cities that sit at higher altitude the cosmic radiation will increase so that it may be a quarter of the background radiation. Flying in an aircraft will raise the cosmic ray dose even further, perhaps ten times that of sea level.

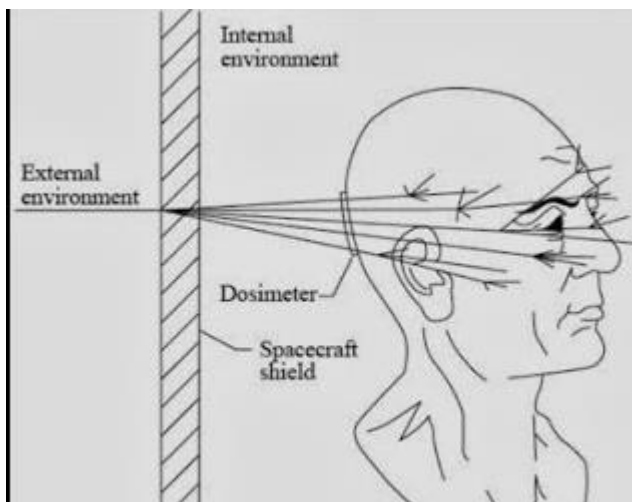


FIGURE 4-9 COSMIC RADIATION (COURTESY NASA)

The very shell of the spacecraft can make the damaging effects of Cosmic rays even worse- hitting the atoms in a thin shell on a spacecraft can cause a cascade of secondary particles which may be even more damaging than the original ray (Figure 4-9).

Cosmic radiation can have several detrimental effects on the human body. One of the primary risks, as with all radiation, is that it increases the chance of cancer. Other effects are cataracts and reduced fertility for men and woman, as well as possible damage to the fetus for pregnant woman.

What is an acceptable level of radiation? This is partly determined by the risk tolerance of the crew and mission planners. In one study, based on looking at a variety of published literature settled on a limit of 20mSv/yr for the general population and 6.6 mGy/yr for pregnant woman (Globus, Orbital Space Settlement Radiation Shielding, April 2017, p. 1). The two terms MSv/yr and mGy/yr are a measure of biological radiation damage and a measure of radiation respectively.

On earth, we have two primary ways of protecting ourselves from cosmic rays- electromagnetic deflection (as done by the earth's magnetic field) and shielding, as done by the Earth's thick atmosphere. Our magnetic field tends to drive these particles away from the mid latitudes of the earth and direct them to the poles. Even more importantly, the Earth's thick atmosphere provides the equivalent of 10t/m² of mass shielding (Johnson & Holbrow, 1977, p. 44) . The atmosphere slows down relativistic particles down to less damaging energies and secondary particles. Nonetheless the radiation levels on earth vary considerably, driven by altitude or the prevalence of other local, non-cosmic ray sources of radiation like Radon.

Electromagnetic deflection has never been used on any spacecraft and brings a whole host of problems. The Earth's magnetic field is rather weak but very extensive- it operates thousands of kilometers out giving a chance to deflect any but the most energetic particles to the poles. A ship or space station with electromagnetic deflection would not have this luxury... its magnetic shield will be much smaller and would therefore have to be much stronger to divert these relativistic particles. Furthermore, protons from solar cosmic rays are relatively easier to deflect. Galactic Cosmic Rays (GCRs) have much higher energies and are more difficult. In one estimate a one megavolt system could reduce solar cosmic rays by 50% but a five megavolt system would reduce the much more difficult GCRs by only 25% (Kelvey, The Harshest Reality, 2023)- meaningful but not a total solution.

Physical shielding is simpler to execute but the amount of shielding to bring the cosmic ray damage down to near earth levels depends on the materials used and the thickness of the shielding. The best materials to use have a large amount of hydrogen in them which tends to reduce the reactivity of the secondary particles. The most effective materials for shielding are high in hydrogen so water or plastic (polyethylene) are the best candidates (Globus, Orbital Space Settlement Radiation Shielding, April 2017). As can be seen in the attached chart, lunar regolith, which was proposed to be used for shield during a 1975 Space Settlement conference, is a poor material, requiring over twice the tonnage per m² to get the equivalent shielding that water and plastic provides. Metals turn out to not to be very good at stopping cosmic rays either. They have the added disadvantage of being very heavy. Hydrogen, Water and are frequently less than 1/5 the weight of metal. Even with the best, lightest shielding, the thickness, and hence weight, of the required shielding material is substantial. Depending on what is determined to be the permissible exposure limits for humans during the voyage, the protective barrier will mass between 6-15 tons per m² and at least 6-7 meters thick! This will be a major design feature for a manned starship and will add tremendously to our mass.

! This will be a major design feature for a manned starship and will add tremendously to our mass.

	polyethylene		water		lunar regolith	
tonnes/ m ²	mSv/yr	mGy/yr	mSv/yr	mGy/yr	mSv/yr	mGy/yr
~0	462	128	462	128	462	128
1	194	85	200	86	281	110
2	137	52	147	54	275	82
3	91	31	101	34	240	62
4	57	18.5	67	21	194	48
5	35	10.9	43	12.5	149	37
6	21.0	6.3	26.5	7.5	109	28
7	12.3	3.6	16.1	4.4	77	20.9
8					52	15.1
9					34.9	10.5
10					22.8	7.1
11					14.5	4.7

**TABLE 4-4 SHIELDING THICKNESS VS RADIATION EXPOSURE LEVELS
(GLOBUS, ORBITAL SPACE SETTLEMENT RADIATION SHIELDING, APRIL
2017)**

Chapter 5- Saturn V and Skylab- 2030's

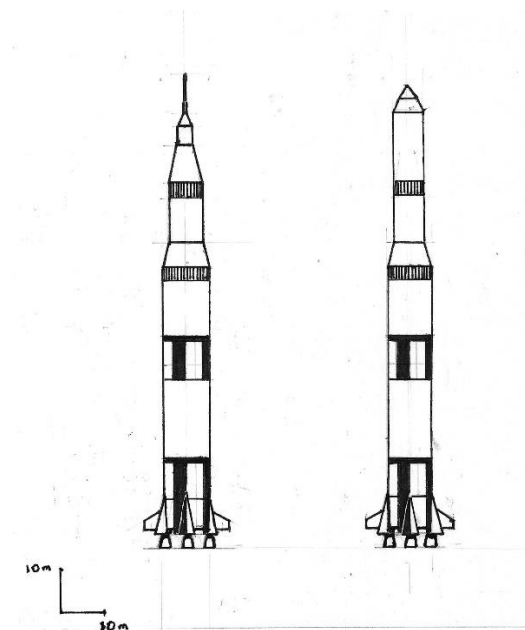


FIGURE 5-1 SATURN V (APOLLO), SATURN V (SKYLAB)

In our first iteration of a starship we will use only proven technology and consider an old design. I begin with a fanciful question of if we could put a fully loaded Saturn V into space and launch the rocket, how fast would we go? Could we go to the stars and if so, how long would it take? Even though this is a somewhat absurd approach, it will enable us to begin using the tools we discussed including the rocket and orbital equations. This exercise will also serve as a baseline for some of our future designs.

When I first drafted this book in 2021/2022 the Saturn V was the largest, most powerful rocket ever built and launched into orbit successfully. At 110.6 m tall and 10.1 m wide at the base it was as tall as a 35-story building. Saturn V's were launched beginning in 1968 with the last flight lifting off in 1973. They were used primarily for test flights and lunar missions, as well as a single mission (the last one) to orbit a space station. Note that the Saturn V got more powerful in later iterations. The specifications I used are for the latest version and are rounded and may differ slightly from other published documents.

The fully loaded and fueled Saturn V weighed a little less than 3 million Kg at liftoff. Its payload to orbit was a tremendous 140,000 kg (140 MT)- or the equivalent of 5 fully loaded tractor trailers or about 100 standard automobiles. Between 1968 and 2024, except for the Space Shuttle, and two flights by the Soviet Space Shuttle equivalent, the Buran, no other rocket even came close. In 2024 Elon Musk's Starship finally exceeded this thrust by nearly 2x (there was a test flights in 2023 but this was suborbital). Currently the most powerful rocket in use is Space X's Falcon Heavy which lifts into orbit a little more than 1/3 of what the Saturn V could do. If successful, the SpaceX Starship will go into service by 2025.

As mentioned in Chapter 2 to reach orbit around the earth you need to achieve a velocity of almost 8 km/s. In everyday life, 8km/s is fast- very fast. You could travel from NY to Chicago in about 150 seconds or two and a half minutes. The Saturn V was so large and powerful that it was able to accelerate 140,000 kg to this speed.

But how big is a Saturn V compared to other engineering works? Compared to modern aircraft, she would weigh the equivalent of 5 fully loaded Airbus 380's (the world's largest commercial aircraft), or about 8 747's (for almost 40 years the world's largest commercial aircraft). The Saturn V had to lift this huge weight off the ground vertically strictly on the thrust of its 5 massive F-1 engines. At lift off the Saturn V burned a tremendous 13,400 Kg of fuel every second- which was ejected out of the rocket engines at about 3000 mps. Using the equation for energy from Equation 2-6-

EQUATION 2-6 $E_k = \frac{1}{2}mv^2$

$$E_k = \frac{1}{2}(13,400kg)(3000mps)^2$$

$E_k = 60,000,000,000 \text{ joules}$

Power is then 60 Gigawatts, or similar to peak energy demand in the United Kingdom (Woods, How Apollo Flew to the Moon, 2011, p. 79).

Another way of looking at it is how much power was required to accelerate 140,000 MT into orbit.

$$E_k = \frac{1}{2}(140,000kg)(8000mps)^2$$

$E_k = 4,480,000,000 \text{ joules}$

This is 4,480 Gigawatts of power required to get this payload into orbit. In reality, it takes about 8 minutes to accelerate into orbit. Dividing these joules by the number of seconds to get to orbit works out to about 9.333 Gigawatts per second- far less than the amount of power that the Saturn engines generated at liftoff- but an impressive number, nonetheless. This discrepancy is mostly caused by the fact that this energy calculation is only the energy of the final payload- during most of the rocket's acceleration the rocket is far heavier- we are accelerating a lot of fuel and oxidizer that will not get to orbit. As Saturn ascends, the second and third stages are far smaller and provide far less power and our ship gets rapidly lighter.

Even though the Saturn V is a massive spaceship, compared to sea vessels, at 3000 MT she would be small. The largest ships ever constructed are on the order of 500,000 MT fully loaded. A nuclear-powered aircraft carrier is on the order of 100,000 MT.

The Specifications for the Saturn V evolved and improved over the duration of the program but if we use the last lunar mission the specifications are as follows:

	First Stage	Second Stage	Third Stage	Totals
Mstructure	130	40	13.5+45	223
MPropellant	2160	456	109.5	2,704
Mtotal	2290	496	123+45	2,954
lsp	263 sl/304 vac	421	421	

Ve	2.58/2.98	4.13	4.13	

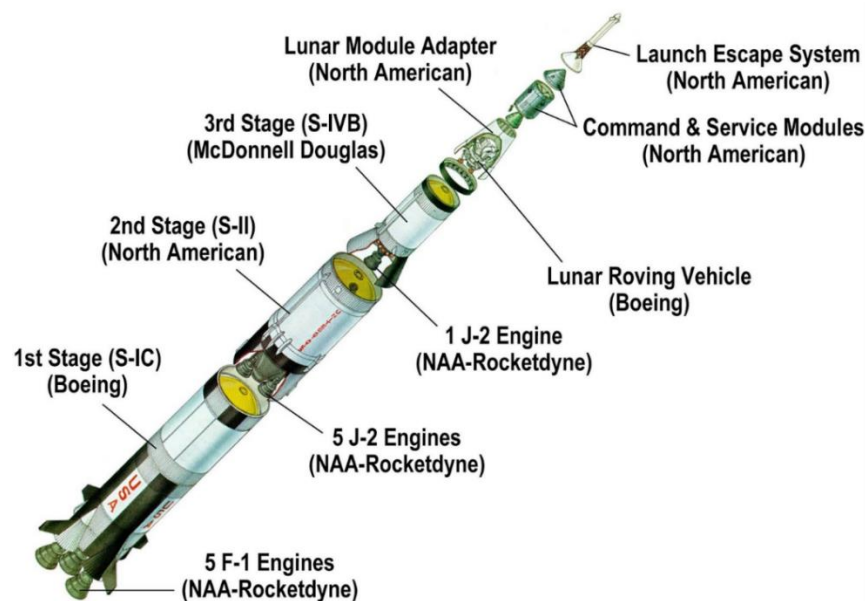
Table 5.1- Saturn V Mass and Specifications (Orloff, 2004)

The Saturn V 140,000 kg payload included the full weight of the Lunar and Command modules as well as the partly fueled third stage. The third stage was not empty of fuel when it reached low earth orbit but used its remaining fuel to leave this orbit and begin the Lunar and Command modules journey to the moon.

In our imaginary exercise, instead of launching from Earth Surface, the fully loaded Saturn V was already in orbit? As described in Chapter 3, instead of wasting all that fuel and energy to rise from the earth and accelerate to go into orbit, you were to use the fully fueled and loaded Saturn VB to launch toward a star? How fast would you go and how long would it take? What are some of the positives of launching from space vs launching from the ground?

There are several items that we discussed in Chapter 2 that would increase the performance of our rocket if launched from earth orbit as compared to the original Saturn V 's that were launched from Florida. They are:

- Gravity Loss
- Atmospheric Drag
- Engine Efficiency



The Saturn V engines were designed for the altitude pressures that they would operate the longest in. Because of this, the First Stage F-1 engines were optimized for close to sea level pressure. For the reason mentioned in Chapter 2, engines will operate more efficiently at higher altitudes- so even the F-1 engine would operate with a higher Isp if ignited in a vacuum due to the portion of thrust provided by the excess nozzle area pressure term.

However, its nozzle would be severely underexpanded- the

FIGURE 5-2: EXPLODED VIEW OF THE 3 STAGE SATURN V (BOEING, 2018)

relatively short nozzle of the F-1 would not extract as much energy as that of an F-1 designed for a vacuum. The Second Stage engines on the other hand were designed to operate at close to a vacuum- by the time the first stage expended its fuel, and the second stage ignited the vehicle was at about 70km. Finally, the third stage, with a single large nozzle, was designed to operate in a vacuum and its Isp was identical to the second stage.

With these factors taken into account, how fast would our imaginary space launched Saturn (to distinguish it from the ground-based Saturn V we will call it a Saturn VB) travel?

Using the specifications for the original rocket we can take the formulas from our rocket discussion in chapter 2 and derive a theoretical speed.

To figure out how much mass is used and what the appropriate weights are, we would have the following:

Initial Mass (all masses are in 1,000 kg)	2954
Stage 1 Fuel used	<u>-2160</u>
Rocket with Stage 1 Empty	794k
Stage 1 dropped	<u>-130</u>
Remaining Rocket mass on Stage 2 ignition	664
Stage 2 Fuel used	<u>- 456</u>
Stage 2 fuel cutoff	208
Stage 2 dropped	<u>-40</u>
Remaining Rocket mass on Stage 3 ignition	168
Stage 3 fuel used	<u>- 28</u>
Final Mass	140

Now let's calculate our speed from each stage

Stage 1

As can be seen from Table 3.1 the total spacecraft weight would be 2927. As noted, though the Sea Level performance of the F-1 had an Isp of 263 the same engine would operate at an Isp of 304 in a vacuum. Therefore, we will use the Isp in a vacuum with its higher performance. We will also assume that we use all of the Stage 1 fuel, or 2160 mt (in reality, there would always be a small quantity of oxidizer and fuel left in the tanks).

Our final weight at Stage 1 burnout would be $2954 - 2160 = 794$

Using our rocket Equation 3-3 $\Delta V = v_e \ln \left(\frac{m_0}{m_1} \right)$

$v_e = 304 * 9.81 = 2,982$ mps or 2.98 kps

$m_0/m_1 = 2954/794$

$\Delta V_1 = 3.92$ kps

What is interesting to note is that this number is significantly higher than that was achieved by the Saturn V. At first stage engine cutoff the velocity of the Saturn V was approximately 9000 fps, or about

2.740 kps. This is due to the fact that our Isp in a vacuum was almost 16% higher, and that there would be no gravity loss or atmospheric drag (including the need to pass through max Q).

Stage 2

Since the fuel for Stage 1 is all gone, we can dispose of the first stage empty weight. While this does not by itself add any speed, it makes the velocity increase greater for the Stage 2 engine burn. From Table 3.1, and eliminating the empty Stage 1 mass of 130 we get the following:

We will use all the fuel of Stage 2, or 445.

Our initial weight at Stage 2 start would be $481+163= 664$

Our final weight at Stage 2 burnout would be $664-456= 208$

Using our rocket equation and an exhaust velocity of 4.13 kps:

$$m_o/m_1= 664/208$$

$$\Delta V_2=4.79 \text{ kps}$$

$$\text{Total speed is } 3.92+4.79= 8.85$$

Stage 3

Stage 3 is a little more complicated. In the original Saturn V when stage 3 and its payload reached orbit, it still had fuel on board. This fuel was used to push the payload to the moon. In this case, since we want to keep our end mass at 140k kg, we will assume that instead of additional fuel the third stage has additional supplies or equipment.

Our initial weight at Stage 3 start would be 168,000kg after we dropped the 40,000 kg empty second stage. To bring us down to our target of 140,000 kg means we will only use 28,000 kg of fuel.

Using our rocket equation:

$$m_o/m_1= 168/140$$

$$\Delta V_3= .77$$

$$\text{Adding the } \Delta V \text{ of the three stages we get: } 8.85+.77= 9.62 \text{ kps}$$

As we can see, this velocity is about 20% more than the speed required to reach orbit- a much higher performance than the actual Saturn V achieved. As mentioned, most of this is due to the improved efficiencies in the first stage caused by the higher Isp when operating in a vacuum and the fact that we did not have to contend with aerodynamic or gravity losses.

In our starship scenario, our Saturn V is already in orbit when we light the first stage. The earth's escape velocity is 11.18 kps but our rocket is already in orbit at a speed of 8kps. If we launched from low earth orbit, our orbital velocity, combined with our Δv would bring our speed at engine burnout to almost 18kps which is more than enough speed to permanently escape the earth's gravity. We would lose some

of this speed as we climbed out of the earth's gravity well and the actual final velocity with which we would leave the earth can be calculated by:

$$\text{EQUATION 5-1 } v_{\infty}^2 = V^2 - v_e^2$$

$$= (9.62 + 8)^2 - 11.18^2 =$$

$$v_{\infty} = \sqrt{(310 - 124)} = 13.64 \text{ KPS}$$

However, the situation is even more complicated, for as discussed in Chapter 1, even if you escaped the earth's gravitational pull you still need to escape the sun. At the earth's distance from the sun, you would require 42 kps to escape into interstellar space. In a situation analogous to our example of breaking out of the earth's orbit by taking advantage of our orbital velocity, if you are willing to head in the exact same direction as the earth's orbit around the sun we can take advantage of the earth orbital speed of just under 30 kps so we would only need about 12 kps to reach the solar system escape velocity. With this constraint, our 13.64 kps rocket would just barely escape the sun with a final velocity of about 7.4 kps. If you chose a path just slightly different than the elliptic and did not take full advantage of the earth's orbital speed, you might not even be able to escape the solar system at all. Also, it should be noted that for an object orbiting the earth, they will usually not be orbiting along the plane of the ecliptic. The earth is tilted at about 23 degrees so an object orbiting at the equator will not line up with the ecliptic except for twice a year when your equatorial satellites orbit would be positioned to take full advantage of the nearly 30kps earth motion.

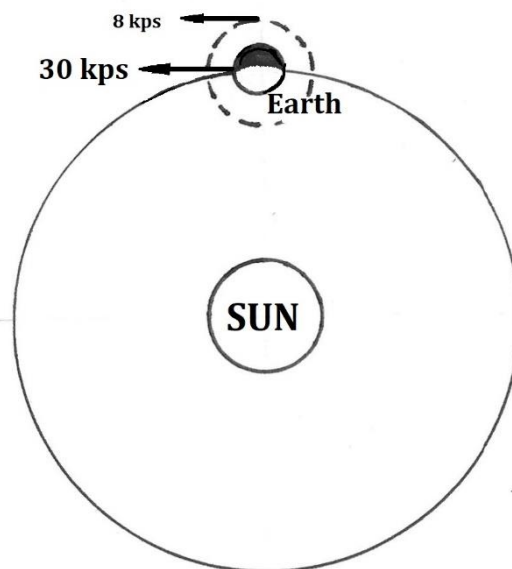


FIGURE 5-3 ORBITAL VELOCITY

Finally, one of the advantages of staging is that it enables very high mass ratios. In our example we wanted to propel a payload of about 140,000 kg to the stars. With a Saturn V we have a relatively small payload and light third stage that would still have a lot of fuel on board. The mass of our empty third stage and our Apollo and Lunar modules is only 58.5 mt. If we relaxed our 140 mt payload constraint and used up all our fuel the third stage final performance would be considerably more.

$$m_o/m_1 = 168/58.5$$

$$\Delta V_3 = 4.36 \text{ kps}$$

This would give us a $\Delta V = 8.85 + 4.36 = 13.21 \text{ kps}$. This is far higher than the 9.62 kps of our original simulation.

Mission

There are two routes we can pursue with our Starship- manned or unmanned. This chapter considers primarily unmodified legacy spacecraft which were designed as purely manned probes. Because of this we will keep our emphasis on what kind of power and supplies would a manned mission need. In Chapter 6 we will consider a tailor-built starship and will investigate what sort of instrumentation would be included, the mass as well as the power requirements.

The Saturn V was used for two primary type of missions- the lunar missions, and the single launch of the large Skylab space station. If we used either of these configurations, what would their capabilities be?

Saturn VA- Apollo design

Could the original Apollo Command and Lunar modules be used for a manned mission to the stars? Of course not. The overall rocket was designed for a two-week maximum mission. The Apollo mission to the moon was powered by Fuel Cells of limited duration, its living area was quite small (6.2 m² of space), the capsule did not recycle water (or anything else), had extremely limited storage, and had a limited oxygen supply. The original design is clearly inadequate.

As shown in Table 3.1 we see that even though the fully loaded Saturn V third stage to the moon was 168,000 kg, 110,000 kg of this was fuel. The remaining cargo was the weight of the third stage (13,500 kg) and the weight of the payload (45,000 kg). With our payload and empty third stage weigh 58,500 kg and we have a total of 140,000 kg to play with, this means we could bring along 81.5 mt of supplies, instrumentation etc.

As can be seen with our interstellar version of the Saturn V Apollo we would have mass available for a very large quantity of supplies, but the constraint is that the Apollo capsule would not be large enough to carry them, not to mention that beyond a short mission the command and lunar modules would become extremely claustrophobic. It would not be practical to modify the Apollo Command and Lunar modules for a deep space mission.

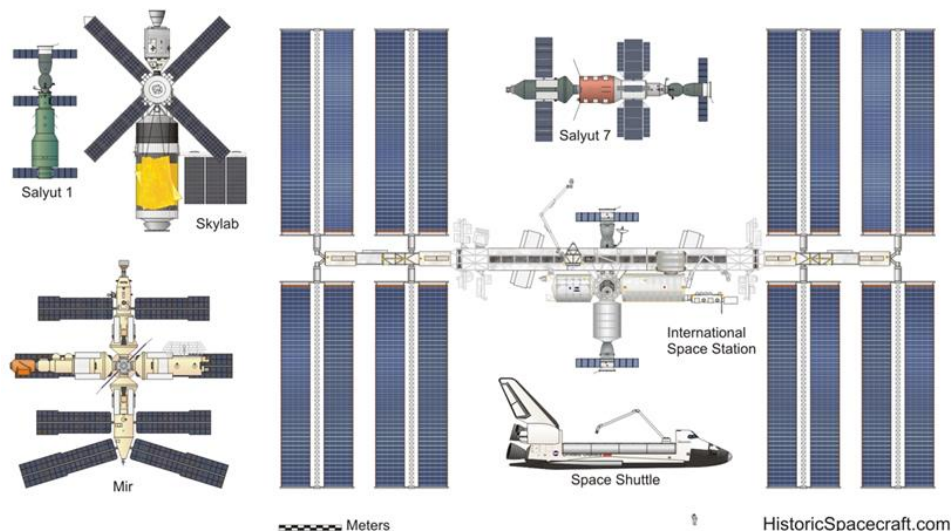


FIGURE 5-4 THE EARLY SPACE STATIONS TO SCALE (HISTORIC SPACECRAFT, N.D.)

We also need to determine how much power our spacecraft would need? The original Apollo spacecraft used Fuel Cells to generate power. Fuel cells combine Oxygen and Hydrogen and produce water and Power. The Apollo spacecraft to the moon functioned on only about 1500 watts of power for their 6.2m³ spacecraft.

A final consideration for any spacecraft going forward is that Apollo had no recycling capabilities (for water or waste of any kind) so you would either have to eject it outside of the spacecraft (which it was not designed for) or bring all your waste along with you. Where would all this waste be stored? Bottom line the Apollo Lunar and Command modules are not suitable for use as starships.

Saturn VB- Skylab

Skylab was a modified third stage that was placed into orbit in 1973. Skylab would be a far better option for a deep space mission than the Apollo Command and Lunar Modules. Skylab's empty weight was 76,540 kg. If we were to send a Skylab to the stars, it would be much more suitable for our journey than Apollo. Keeping it as designed at 77mt mass we could carry about 63mt of expendables or supplies. Since Skylab is so much larger than Apollo, it would be much more comfortable for longer voyages, and would have a lot more room for the storing of food, water, and supplies. One of the problems with Skylab would be the fact that it WAS the third stage- it had its engines removed. Because of this it would not be able to be launched into deep space. For our exercise let us assume that like Apollo we have a fully loaded Skylab of our targeted 140mt mass and that has been boosted by Saturn's first and second stage into an interstellar trajectory. The Saturn first and second stages would have only given us 8.85kps velocity.

Skylab contained a large habitable manned portion of 352 m³ for three astronauts- or over 100 m³ per person. Most of this habitable portion was in the so-called Orbital Workshop which was 14.7m long by 6.6m in diameter. The workshop portion mass was only 35,000kg.

Water, Oxygen and Food

People on Earth consume about 3.7 liters of water a day- or 11 liters for a crew of three or 78 liters per week. In space, they can consume significantly less- only about 2.6 liters per day which includes water in the food- for a total of only 55 liters per week (NASA, 1991). These figures do not include bathing or anything else. If we add 4 liters of water per week per person for a weekly bath/shave, then we raise water usage to about 67 liters per week for our three-person crew. Neither Apollo or Skylab recycled any water (or anything else) due to the length of the missions where it was determined the extra complexity of trying to recycle was not worth the technological challenges.

Using the above consumption number for water we would use about 3500 liters, or 3500 kg of water per year for a crew of three. It becomes obvious why they did not recycle for the short missions of Apollo (never going over 10 days) and the maximum Skylab duration of 84 days (12 weeks)- they simply did not need to.

Food would also be required. If we use the attached estimates for dried food of 1.77 kg, then each week a crew of three would consume about 37kg of dried food- or about 2000kg per year for a crew of three.

One complexity that we have not considered is what to do with all the human waste generated because what goes in must come out. Many of the early missions just returned the waste with the astronauts for study. For longer missions the waste

Life Requirements on Earth and in Space				
Item	On Earth		In Space	
	kg per person per day ¹	gallons per person per day	kg per person per day ²	gallons per person per day
Oxygen	0.84		0.84	
Drinking Water	10	2.64	1.62	0.43
Dried Food	1.77		1.77	
Water for Food	4	1.06	0.80	0.21

TABLE 5-1 (NASA, 1991, p. 5)

was discharged into space. The problem with this is that each time the waste is discharged, it also discharges water, as well as some atmosphere.

Technology- Power- Fuel Cells and Solar

Power will be a problem on any mission, but certainly a substantial one for a starship whose voyage may last for many decades or centuries. For a mission of just a few years it should be a much more manageable problem (we will discuss more power options in Chapter 6).

The two most common sources of power when Apollo and Skylab were launched were Fuel Cells and Solar Panels. We will consider the positives and negatives of both. A purely automated mission could suffice on only a few hundred watts of power. For a manned mission, more power would be required to keep the crew comfortable. As can be imagined, the technical challenges of a manned spaceship are far more extreme than an unmanned probe. We have many unmanned probes that have functioned for 50 or more years. For automated deep space probes, the main problems are the gradual diminishment of power from their nuclear fuel (more on that in Chapter 6) and the exhaustion of their maneuvering fuel.

For an automated mission, depending on the instruments chosen, no more than a few hundred watts of power would be needed to run our instruments. Of greater concern is the power needed to transmit and receive data. As you get further from the earth your transmitter power needs to either go up substantially (as a square of your distance) or the area of your antenna needs to increase (also as the square of your distance) or both. This will be discussed in Chapter 6.

In Appendix C we list a few typical unmanned spacecrafts with an emphasis on the interstellar ones- the ones that are leaving the solar system. As can be seen, the actual mass of the instrumentation as well as the amount of power needed is very small. Frequently most of the spacecraft's mass is the structure, power supply, and the maneuvering fuel and the instrumentation only required a couple hundred watts.

Even the 1500 watts that a very small manned spacecraft like Apollo needs is far more power than required by an automated spacecraft.

Solar Panels

Skylab, unlike Apollo, was designed to operate with three astronauts for months at a time. Skylab had an early version of Solar Panels which generated about 12kw of useable power which, after charging the batteries, voltage, and power regulators, provided about 8kw (Stuhlinger, 1973). As you can imagine, for a voyage into deep space solar power is not viable. While modern solar cells are much more efficient and lighter than those on Skylab, they still need to be positioned at a reasonable distance from the sun to generate power. The farthest spacecraft have traveled with Solar power is Jupiter. Even at this distance the sunlight intensity is only around 3.4% of earth. At earth's distance from the sun the Juno probe could generate 14,000 watts. At Jupiter it was down to 435 watts. At Saturn the power would be down to little more than 100 watts.

How heavy would solar panels be? Solar Cells have continued to improve in efficiency while growing lighter. On the ISS, a solar cell "wing" that generates about 60kw weighs 2400kg (Mansfield, 2006) or 25W/kg. The Juno spacecraft to Jupiter solar panels weigh about 750 lbs. (341kg). This works out to about 35W/kg at earth distance.

Fuel Cells

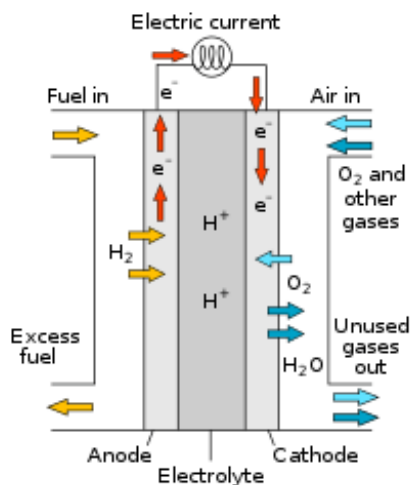


FIGURE 5-5 FUEL CELL

Apollo lunar missions depended on Fuel Cells. Apollo carried tanks of hydrogen and oxygen, combined them in a cell, and out came power and water... a lot of water. Indeed, if we used fuel cells it turns out we would not need to bring along water... the fuel cells will generate more than enough water for the crew.

The first question we need to answer is how much power do we need? If using the Apollo command module, 1500 watts was adequate. If we could send a larger vessel with more room and amenities, we would need more power. The ISS generates (for a spacecraft) tremendous amounts of power- up to 900,000 watts (90kw).

Power requirements are driven by the number of crew, the size of the habitat, and the nature of the work done. The ISS is even larger than even our Skylab- about 915 m³ of livable space vs the 352 m³ on Skylab. Our Apollo spacecraft had only 6.2 m³. The

ISS can also host up to 7 astronauts, but Skylab was designed for only 3. Nonetheless, Skylab provided a much larger, more comfortable experience than Apollo and any mission with a few astronauts would like use more along the power of Skylab.

How much hydrogen and oxygen are required to generate 8000 watts if we used a fuel cell? Hydrogen has a value of 33 kwh per KG (Fung, 2005)- For a fuel cell that is 50% efficient you would generate about 16.5 kwh per kg.

	Saturn V Fueled	Saturn V Structure and payload (no fuel)	Saturn VB Skylab Unmodified	Skylab Starship (optimized with fuel Cells)
Stage 3 booster/Skylab	123,000 (70,280 in orbit)	13500	76,540	40,000
Command Module	28800	11900	NA	NA
Service Module (including Fuel)	24520	6200	NA	NA
Lunar Module	16400		NA	NA
Water			(NA- provided by Fuel Cells)	(NA- provided by Fuel Cells)
Food			2960	4,660
Fuel/Power			60,480	95,250
Total	140000		140000	140000

TABLE 5-2 SKYLAB DERIVED STARSHIP MASS

For our target of 8000 watts, you would therefore use about .5 kg of hydrogen per hour. To operate the equipment for 1000 hours (about 40 days) you would need 500 kg hydrogen. For a 20-year mission you would need about 91 mt of hydrogen. Water has two atoms of hydrogen for each atom of oxygen, but the atomic weight of oxygen is 16 times that of hydrogen therefore you will need 8 times more Oxygen by mass than hydrogen- or an impressive 730 mt. Combined Hydrogen and Oxygen usage per hour works out to about 4.5kg/hr. or 756kg per week. This water generated can be used in lieu of the water we brought along for drinking, food, and hygiene (indeed it is far more than we need) but the savings in not bringing along any water to consume is more than offset by the fact that in addition to the mass of Oxygen and Hydrogen, you must add in the mass of large, insulated storage tanks to store these cryogenic materials. It should also be noted that the Skylab unmodified mass included specialized airlock module, the multiple docking adapter, and the Apollo Telescope Mount. Most if not all this mass could be eliminated for our Starship. If this were done, we could reduce our empty mass to 40,000kg (by eliminating the 35,000 kg Orbital Workshop plus 5000kg for solar panels and an airlock). This would permit us a couple more months of voyage time. If we had a 40mt spacecraft we would have available 100 mt for food and Oxygen/hydrogen.

Plotting the empty vs target mass with the consumables (food and hydrogen/oxygen) used we get this graph, which clearly shows that the dry food consumed is very small while the amount of water created

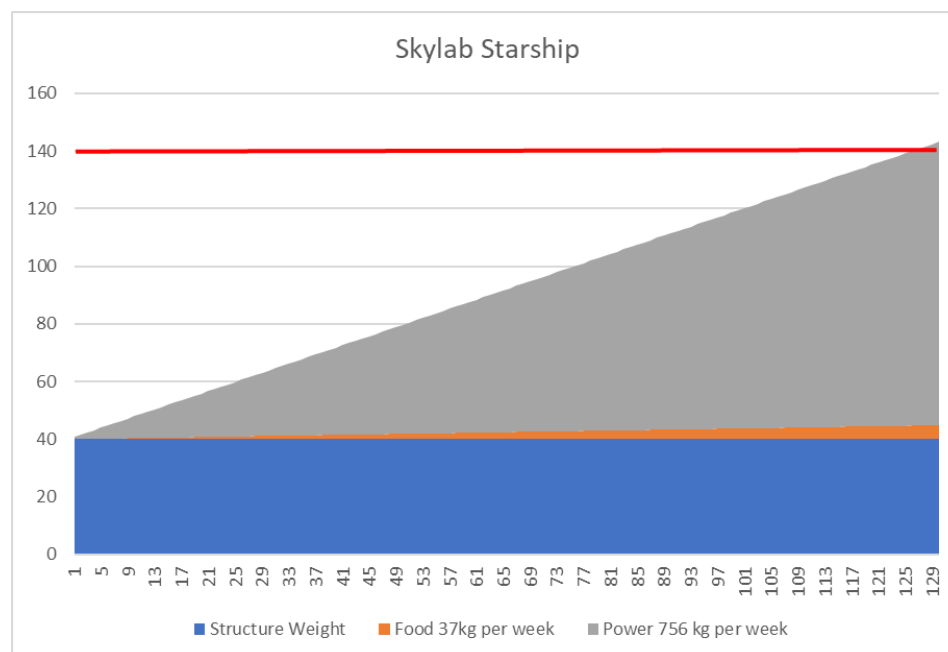


FIGURE 5-6 SKYLAB DERIVED STARSHIP MISSION DURATION

from the power generation is very large. In this case your spacecraft mission duration will be limited to the amount of oxygen and hydrogen you can carry. This would restrict our mission to about 126 weeks- or about 29 months. In short, using fuel cells provides plenty of water for food and our crew, but our mass limitations would keep the crew alive for little more than two years.

Cost

Since we made a baseline assumption that a Saturn V was magically placed into orbit, no thought was made as to whether this is practical or possible. The reality is that it would be very impractical to launch a Saturn V into orbit with any of our current launchers since the Saturn V is size wise far bigger than any current rocket payload fairing diameter. It would have to be launched in many pieces, and since the rocket was never designed to be assembled in space, it could not be done without major redesign in which case it would be considered in our next iteration- the Saturn VI. For example, the first and second stage of the Saturn V are about 11 meters in diameter. Most rockets in existence right now have payload fairings that are limited to 5m in diameter. The future Space X Starship is planned to have a 9m diameter payload bay so even this would be too small to be able to launch the Saturn V even if it was broken up into sections. Furthermore, any sections that would be launched would have to be assembled with great difficulty in the zero gravity of orbit, including welding and bolting. A large assembly space station would undoubtedly be required. It should be noted that there has never been welding done in both the vacuum and zero gravity of space and its feasibility is unknown.

Notwithstanding this, assuming the Saturn V could be disassembled and launched and then reassembled in space, how much would such an endeavor cost?

With the advent of Space X launch costs have dropped considerably over the last ten years. Referring to the graph in Chapter 4, costs can be seen to vary considerably but with Space X the Falcon Heavy is

shown to be somewhat less than \$2000 per kg. Using the Space X published costs for a Falcon Heavy of \$90 million for 63800kg to low earth orbit equates to about \$1410 per kg- probably the lowest we can reasonably expect in the near future with current launch activity. In reality, launches (even SpaceX ones) usually cost much more because of requirements for certain orbits, launch windows, fairing costs and other special requirements. Regardless of the cost to launch, the actual payload mass that can be put in orbit is relatively small for even the largest rockets. To launch a 3,000,000 kg Saturn V in orbit would require about 47 Falcon launches! With that many launches you should be able to have some economies of scale (unless the program is run by the government) so I choose to keep the average launch price of a Falcon Heavy at the low \$90 million. Using this the price of 47 launches alone would cost \$4.23 billion. You would have to send up additional equipment (space station, assembly equipment, supplies, tools) and astronauts to assemble and fuel the rocket. It would probably be reasonable to double the number of launches required so the launch costs alone would be \$10 billion.

Since the Saturn V has already been designed not many Research and Development dollars would need to be spent. However, even with an already developed spacecraft, we would certainly have to figure out how to break the ship up into pieces small enough to be launched and figuring out how to assemble them again in orbit- no small feat as the original Saturn V was not designed to be broken into launchable pieces. Furthermore, even assuming the plans for the Saturn V are still in existence, the manufacture of the spaceship would be additional tooling costs.

Most of our 47 launches would bring up your fuel and oxygen- which is in itself a challenge. Specially designed insulated tanks or bladders would have to be built to carry the fuel or oxidizer. The first stage fuel, Kerosene, is relatively easy to store and handle. For stages 2 and 3, hydrogen is used for the fuel. As we shall see in Chapter 6, hydrogen is very challenging to deal with- the small size of the hydrogen molecule means it tends to leak past seals and gaskets, and to make it liquid requires lowering it to just a few degrees about absolute zero. Even in liquid form it is not very dense, requiring very large tanks to store as compared to Kerosene. If we used the SpaceX Starship payload bay to carry this fuel, the SpaceX Starship would have to be modified. The best way to transport the fuel up could either be in lightweight disposable or reusable fuel tanks. Disposable tanks would be used only once, which should reduce design costs, or they can be designed to be brought back to earth inside the SpaceX starship and reused at higher design cost. Designing these tanks would likely be inexpensive but many things would have to be considered, including the boil off of hydrogen, keeping the hydrogen cold and liquid, how to safely vent the hydrogen while preparing for lift off, and during rocket ascent and orbital operations. To a lesser extent oxygen would present similar problems, The tanks would have heavy insulation to minimize boil off, and in the case of hydrogen, it would likely be necessary to actively cool down the hydrogen when in space both while the refueling ship approaches our Saturn V is minimized, or even how to actively cool the oxygen once in space.

While seeing what a Saturn V could do if used as a starship was informative and fun it would not be practical for many of the reasons mentioned. Using the general size and mass ratio of the Saturn V could we design a true starship successor? Since the Saturn V was designed the space industry has advanced considerably in the intervening 60 years, but in particularly over the last 10. The technology in many areas has not advanced radically but we have gotten much more refined. Rocket engines are not more powerful, or their specific impulse much better since that is primarily driven by physics and chemistry- but they are getting more reliable. Even more importantly, Space X is radically redefining the economics of space travel. Furthermore, the creative application of technology has allowed for the ability to launch

huge spacecraft (for example the Starship second stage) into orbit in one shot. With the promise of in space refueling many options that simplify our design permitting a modular and easily assembled starship that can be launched from Earth. We will consider this with our Saturn VI.

Summary and Conclusions

We tried to develop our Saturn VB with no new technology. However, we quickly encountered many major issues:

- Insufficient Speed. Our rocket would achieve about 13 kms on earth departure if launched in the direction of its orbit. At this speed we would take about 200,000 years to travel 10 Ly.
- Excessive Time means our instruments and crew would be deceased by the time we reach our destination. Even if all the excess payload mass available for the Saturn VA were used to carry hydrogen and oxygen for the fuel cells, and we filled the holds with food, a manned crew would only survive a few years. Even with a relatively light 40mt ship, 100mt of supplies (primarily for the oxygen and hydrogen for the fuel cells) our vessel would only be able to generate power for 29 months.
- Difficult construction. It would not be practical to use either the Saturn V as an Apollo Starship or Skylab launcher. The Saturn V, for all practical purposes, could not be assembled in orbit.

In this chapter we did come up with some rules of thumb for designing a ship going forward.

Our Power requirements, if using a Skylab sized habitation module with a crew of three, will be about 8kw of power.

If we have no water recycling, then we have estimated we need 67 liters of water per week for a crew of three. This works out to about 22 liters per person per week.

Finally, we estimated that our food usage for a crew of three would be about 37kg per week of 12kg per person per week.

Our calculated performance for our Saturn V starship are:

	Launch Mass Mo (t)	Empty Mass (t)	Mass Fraction	Specific Impulse	Exhaust Velocity (kps)	Final Startship Velocity (kps)	Type of Engine	Power	Mission Duration	Years to go 10LY	Comments
Saturn V- Apollo	2,970	140	21.2	304/421	2.98/4.13	10.0	RP-1/LOX; LH/LOX	Fuel Cells; 1.5kw	2 weeks	300,000	3 Stage; Limited power/storage
	2,970	30	99.0	304/421	2.98/4.13	13.0	RP-1/LOX; LH/LOX	Fuel Cells; 1.5kw	2 weeks	230,769	3 Stage
Saturn VB- Skylab	3,000	140	21.4	304/421	2.98/4.13	9.0	RP-1/LOX; LH/LOX	Fuel Cells; 8kw	80 weeks	333,333	2 Stage

To reach the stars with either a usable payload or living crew we will need to do better- much better.

Chapter 6- Saturn VI and SpaceX Starship- 2040's

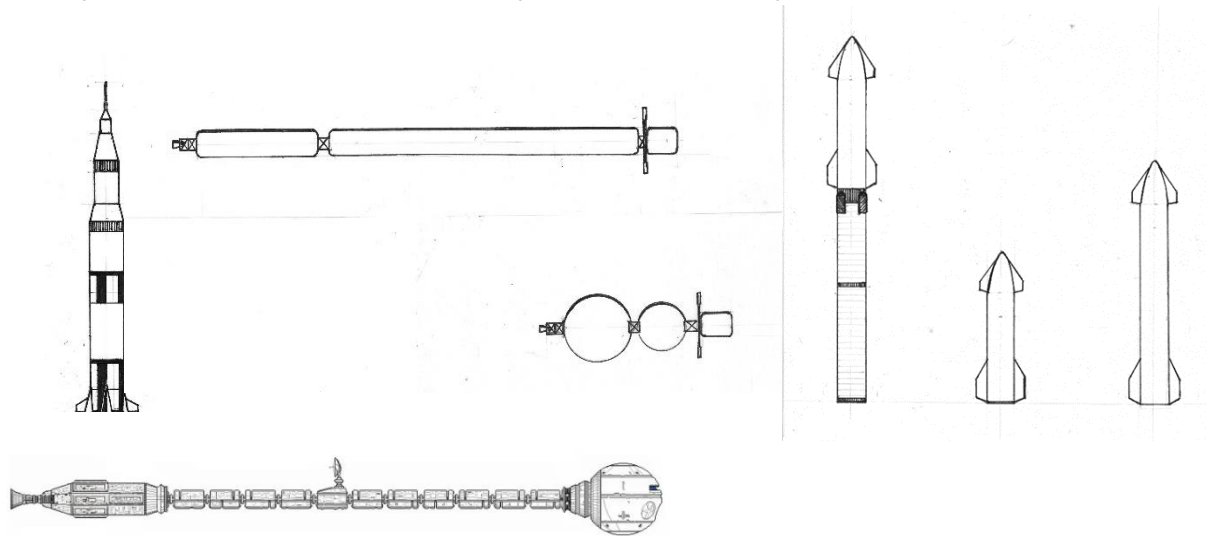


FIGURE 6-1 SATURN V, VIA, VIB, DISCOVERY (2001: A SPACE ODYSSEY), SPACEX STARSHIP V2 AND V3 (TO SCALE)

The Saturn V was a rocket built using technology from the 1960's and designed for a specific mission-sending a small crew to the moon. Surely in the intervening sixty years we can build a far more capable starship using newer technology and specifically designed for an interstellar mission?

Over the next few chapters, so we can compare apples to apples (or starship to starship if you will), I have chosen to round up the weights and the mass ratio of our Interstellar class "starship". We will baseline our rockets to have a fully fueled mass of 3 million kg with a payload will by 150,000 kg for a mass ratio of exactly 20. We will look at an updated spacecraft designed from scratch as well as the capabilities currently being built into the SpaceX Starship. Since the SpaceX Starship is considerably different in design philosophy, I will try to normalize for comparisons, but I will make some exceptions.

Looking at the rocket equation, as well as the performance of our Saturn VA and VB, we realize that normal rockets have nowhere near the capabilities required for rapid star travel. With this chapter I will introduce more modern technologies, a more reasonable and economic design, and use some of the tools that we have already discussed to build a more practical and capable interstellar spacecraft. With the Saturn VI we will start with a clean sheet approach but one that only uses known and demonstrated (though not necessarily flown) technology. Due to the need for some design work, and because we will consider nuclear energy for both power and propulsion, some industries would have to be revitalized and some small technology refinements would be needed. For these reasons I believe a mission of this sort could be done within the next twenty or so years- with a launch in the 2040's time frame.

We will consider the following modifications and refinements in this chapter:

- We will look at the SpaceX "Starship" currently in development to determine its capabilities

- We will follow up with a clean sheet Saturn VI approach that instead of using the RP-1 Fuel on lift as was used on the first stage, we will only consider using only the higher energy fuel of oxygen and hydrogen. As we saw with the Saturn V, liquid hydrogen and oxygen will have greater performance.
- Because we will be launching from space our engines will be optimized for vacuum thrust. With the Saturn V specifically, the first stage was designed for low altitude.
- Related to this, since we are not lifting off from the ground, we will not need the tremendous thrust of the five F-1s. We can accelerate at a leisurely pace with a single engine. Therefore, we will eliminate a lot of unnecessary weight. Since our mass ratio is still 20 this will not help us in our final velocity- but it will allow more mass to be dedicated for payload (including food and water) and make the MR of 20 easier to achieve.
- Instead of having multiple stages we will have one stage with a single engine which will simplify our design and make our empty vehicle lighter. Without launching through a thick atmosphere with high g forces) we will go with a lightweight structure which means more of our 150,000 kg final weight can be dedicated to payload and our power supply.
- We will consider more advanced power sources than the batteries and Solar Panels used on the original Saturn V and Skylab.
- For manned missions we will include water recycling.
- We will use the Gravitational Slingshot technique around Jupiter to see what performance improvements it can provide.
- We will look at some basic costs. Part of this will be making the design as practical as possible. We will consider designing for assembly in orbit. In the original design we magically lifted a fully loaded Saturn V into orbit. This time we will spend a little thought on how we could get the various Saturn VI fuel and components into orbit and assembled as well as some rudimentary costs.

Space X Starship

In the third decade of the 21st Century, there is a new contender for the largest rocket ever built- the Space X Starship. This rocket is likely to undergo considerable upgrades over the next decade so all the numbers used in this chapter represent the latest iteration but will likely change in the future.

As currently proposed, this two-stage rocket will mass when fully loaded at an estimated 5.2 million kg, or 2.2 million kg more than our Saturn V. It stands over 120 m tall. The configuration of the Space X Starship is considerably different than the Saturn V as it is only two stages, where the second stage itself is designed to go into orbit and carry the payload. Because of this, the Starship second stage (confusingly also called Starship) is itself a powerful rocket in its own right and can both take off and land on its own (though it would not be able reach earth orbit without the 1st stage booster). Some versions of the Starship second stage rocket will be designed to be refueled in orbit. This in orbit refueling capability is important in that this spacecraft, once refueled, can accelerate out of earth's orbit and reach other planets. Since the fully assembled rocket is only two stages and the second stage itself is a fully functional rocket or cargo carrier, this design is less mass efficient at getting usable payload into orbit. In addition, the selection of durable stainless steel as the rocket's primary construction material makes the

empty rocket heavier than if aluminum or composites had been used. Even though the Starship lift off mass over two million kilograms more than the Saturn V, its payload to orbit is only about 200,000 kg, of which 100,000 kg is the vehicle itself... so the actual payload is less than the Saturn V (though future upgraded versions will be more powerful). This is not a major issue in real life since the Starship is designed to be fully reusable- and its anticipated launch costs to orbit will be vastly lower than any other

rocket in history. Fuel is one of the least expensive items when launching a rocket- far more expensive are the rocket engines, fuel tanks, associated electronics etc. that traditionally have been used once and dumped into the ocean.

Since the Space X Starship is radically different design than the Saturn V it is impossible to compare apples to apples. A fully fueled second stage Starship has a total mass of about 1400 metric tons of which 1,200 MT is fuel. In my calculations below I have taken the approximate current specifications and calculated the performance. Actual performance will likely be higher since some versions of the second stage are planned to be

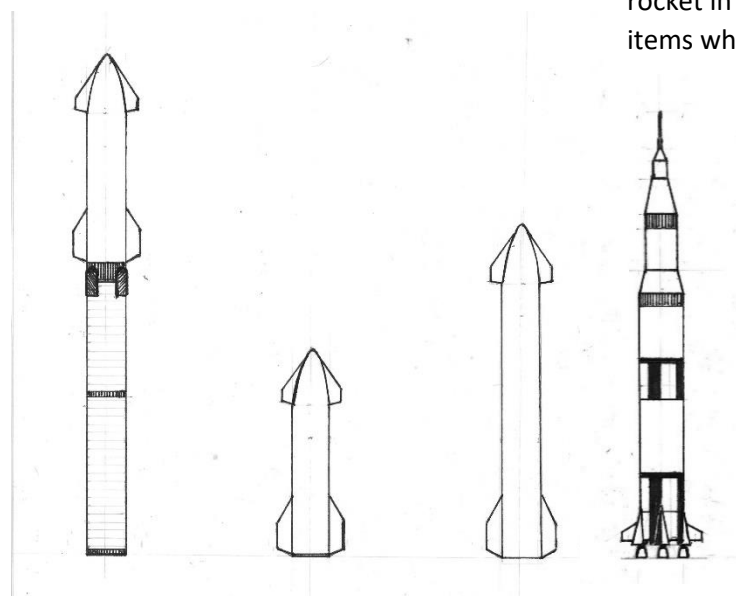


FIGURE 6-2 SATURN V AND SPACE X STARSHIP ITERATIONS TO SCALE

interplanetary or lunar landing ships and will not need to land back on the earth- hence can eliminate the thermal protections system. For the same reason, once in orbit, it will not need to have the six engines as currently designed- three for departing from earth orbit and three for landing back on earth. Indeed, we could consider going only with a single engine which will reduce the starship m1 mass to something less than the planned 100mt.

The Raptor Vacuum optimized engine has a specific impulse of 380 sec- less than the LH/LO engines but much more than the Saturn V's first stage. Based on these specifications we can calculate the theorhetical performance of the Starship.

	First Stage	Second Stage	Totals	
m_{structure} (mt)	200	100(structure)+ 100(payload)= 200	400	Includes 100mt for cargo
m_{propellant} (mt)	3600	1200	4800	
m_{total} (mt)	3800	1400	5200	
MR	5200/1600=3.25	1400/200=7		
Isp (sec)	380	380		
v_{exhaust} (kps)	3.73	3.73		

TABLE 6-1 STARSHIP SPECIFICATIONS

Initial Mass (all masses are in 1,000 kg)	5200
Stage 1 Fuel used	<u>-3600</u>
Rocket with Stage 1 Empty	1600
Stage 1 dropped	<u>-200</u>
Remaining Rocket mass on Stage 2 ignition	1400
Stage 2 Fuel used	<u>- 1200</u>
Stage 2 fuel cutoff	200

Stage 1

Using our Equation 3-3 and substituting 3728 mps for v_e

$$\Delta V = v_e \ln = 3728 \ln\left(\frac{5200}{1600}\right)$$

$$\Delta V = 4390 \text{ mps} = 4.39 \text{ kps}$$

Stage 2

$$\Delta V = v_e \ln = 3728 \ln\left(\frac{1400}{200}\right)$$

$$\Delta V = 7250 \text{ mps} = 7.25 \text{ kps}$$

$$\text{For a total } \Delta V = 4.39 + 7.25 = 11.64 \text{ kps}$$

Therefore, a two stage Starship would be able to achieve a velocity higher than our Saturn V. This impressive performance is mainly driven by the much higher specific impulse of the first stage and the fact that we have a final mass fraction of 5200/200 or 26- much higher than our 20 to one we used for the Saturn V.

Realistically we could not put a SpaceX first stage in orbit, but we could easily conceive of a an enlarged or stretched version of the second stage Starship into orbit. A Space X Starship as a “starship” would be much easier to execute than our Saturn V Skylab as the Starship is designed to be refueled in orbit and, as opposed to the Saturn V the whole second stage rocket is designed as a standalone ship- no space fabrication is required.

The SpaceX Starship second stage as currently designed is not as heavy as our Saturn V nor does it have a 20:1 mass ratio. However, suppose we built a stretched version on earth, with extra-large fuel tanks? This second stage would be heavier than the current Starship, but we could offset this extra weight when launched by eliminating the payload.

Currently the SpaceX Starship second stage is anticipated to weigh 100 mt when empty and would carry 1200 mt of fuel plus an anticipated 100 mt payload for a total mass of 1400mt and a mass ratio of 7 (though Elon Musk has already indicated a 150mt payload for future starships). A Starship with no cargo,

would be only 100mt, and our fuel/oxidizer could be 1300mt. Our MR would now be 14. If we wanted to increase our total Starship MR to 20 and include a 50mt cargo we would have to increase our m0 mass to 4,000mt. This will require us to more than double our fuel capacity to 3800 mt, while raising our empty Starship mass from 100 to 150 mt with a payload of 50mt so we would get our 20:1 mass ratio. This may be doable as we should be able to more than double our tank size without doubling the weight since a portion of our baseline starship mass is fixed, including the 6 engines. Indeed, for a deep space starship we would eliminate five of the six engines since there is no need to land the starship on earth or any other planet for that matter.

Some possible Starship derivatives are shown in the table below:

	Nominal Empty Mass	Payload-Cargo, supplies	Fuel and Oxidizer	Total Mass	Mass Ratio	Δv	Comments
Saturn V Skylab	40	100	2616	2926	NA- 2 Stage	8.85	Two Stage with Skylab derived payload
Starship (2 stage)- stock	100	100	4800	5200	NA- 2 Stage	11.64	Stock 2 Stage Starship theorhetical
Single Starship Stage- stock	100	100	1200	1,400	7	7.25	Stock SpaceX Starship
Single Stage modified	100	0	1300	1,400	14	9.84	Enlarged fuel tanks but kept in same mold line; 5 engines removed. No payload
Stretched Space X Starship	150	50	3800	4,000	20	11.17	Stretched Fuel Tanks; 5 engines removed

TABLE 6-2 SATURN V AND SPACE X STARSHIP COMPARISONS

In the four SpaceX Starship scenarios I made the following assumptions:

- In the first scenario I consider an unmodified 2 stage Starship and derived its performance and compared it to that of the Saturn V.
- In the Single Starship Stage-stock scenario I took an unmodified second stage and showed its performance. This is basically the Starship configuration that Elon Musk plans to send to Mars.
- In the single stage modified scenario I took the basic outside dimensions of a stock Starship, but I removed payload space to add fuel tanks that are about 10% larger. While the current Starship design is still being finalized, it is anticipated the cargo area to have 1100 m³ of pressurized crew space. This is now dedicated to additional fuel. I kept the empty starship mass at 100mt, but this may be pessimistic- we should be able to have a small mass reduction by eliminating some

of the structural elements that the Starship is being built with that would not be needed for our starship. For instance, we would reduce the number of engines from the six that are currently on the Starship (3 vacuum engines and 3 low expansion engines) to one. Our starship would only need one vacuum engine- though with only one engine the acceleration would be much slower, and the rocket would have to burn three times longer. Each Raptor engine weighs about 1500 kg. Eliminating five engines would reduce the empty weight of the SpaceX Starship by about 7500kg. Furthermore, we could eliminate the thermal protection system on the Starship.

- In the final scenario I consider carrying a 50mt payload and stretching the Starship to bring our mass ratio (and mass) up to our target of 20:1. Our final m_0 would be 4000 mt. The reason for the higher m_0 is that I don't believe we could build a stretched Starship with a 100mt empty mass even if we eliminated all unnecessary things like engines and Thermal Protection system. Our ship will need to be stretched to nearly three times its current length with a very small payload area. The Stainless-Steel structure of the Starship is heavy and a 150mt is an aggressive number for a ship with tanks three times the size of a stock Starship. With this configuration I have included provisions for a 50mt payload and raised the m_1 to 200mt.

A SpaceX Starship would be much easier to work with as a interstellar spacecraft since it was designed from the beginning to be an interplanetary spacecraft. As opposed to the Skylab, it has its engines built in and certain versions will be designed to be refueled in orbit.

Initial renderings of the SpaceX spacecraft indicated it would be powered by solar panels. Since we are going into deep space, we would replace these with fuel cells. If we went with a Starship of 100 mt payload for cargo and supplies, using our Chapter 7 derived consumables of about 80kg per week for three astronauts, and included generating 8kw of power, our crew would have enough supplies for about 126 weeks as with the Saturn V with a velocity of about 7.25 kps. For our stretched Starship configuration with a 50mt payload we could survive about 63weeks but would be traveling much faster at 11.17kps.

Physics of Fuel and Oxidizer

The SpaceX Starship, while being the easiest and most inexpensive rocket we could design as an interplanetary spaceship, is not designed for voyages to the stars. It uses Methane engines for several reasons- primarily because Methane is relatively easy to handle (as compared to liquid hydrogen), and perhaps most importantly, can be manufactured on Mars by converting the Martian CO_2 atmosphere to fuel. The Methane/Oxygen (also called Methalox) engines of the Starship have a lower Specific Impulse than our Hydrogen and Oxygen engines.

In general, specific impulses are directly related to the square root of the exhaust temperature divided by the molecular weight. LH and LOX turn out to be one of the best fuel combinations due to their high temperature combustion combined with the low molecular weight of the exhaust product (water). Because of this LH and LOX engines are about the most powerful and efficient chemical engines in existence- and that is why they were used on the first and second stage of the Saturn V as well as the Space Shuttle (SS) and its successor, the Space Launch System (SLS). However, fuels other than hydrogen are usually easier to handle and, since other fuels don't have to be kept as cold, allows for lighter tanks

with less insulation. Hydrogen, with its small atomic size, tends to leak through seals and gaskets. Furthermore, Figure 6-3 shows the differing densities for various liquid fuels as well as liquid hydrogen. Note how cold hydrogen must be to be kept in liquid phase. Also note that for all liquids, the specific gravity (mass per unit volume) increases with a lower temperature- the liquids become denser.

In 2015 Space X started supercooling the liquid oxygen in its Falcon 9 rockets from around 90K to about 70K in order to increase performance (store more oxygen for the same volume). As done by SpaceX, we could chill the liquid oxygen some more and thereby construct a smaller tank. Looking at the chart further cooling oxygen allows for 10-15% more oxidizer for the same volume of tank.

Can we leverage this technique for our hydrogen? Alas, not really. If we use LH, there is not much advantage to further chilling the liquid hydrogen as you are near absolute zero already. Getting even a couple of degrees closer to absolute zero is very difficult and the percentage improvement in density for a few degrees lower does not lead to a reduced structural mass.

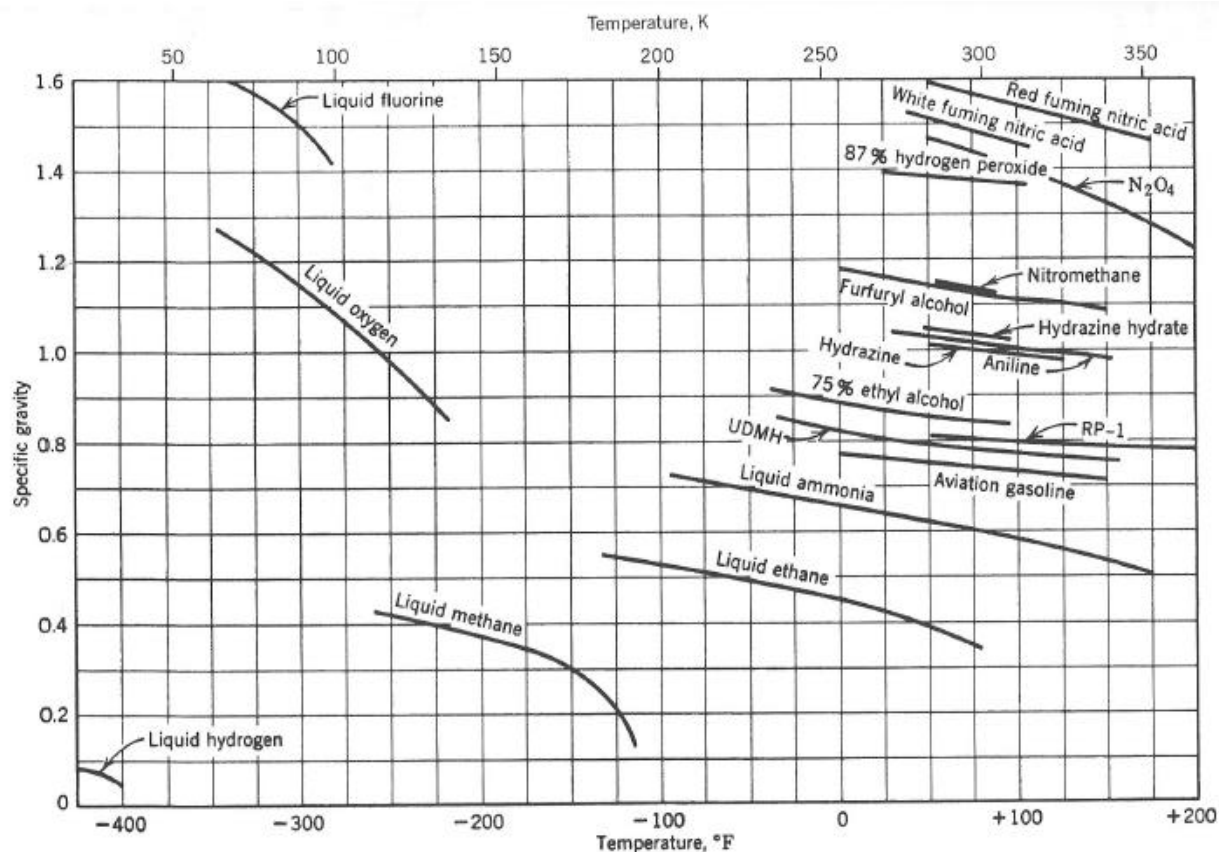


FIGURE 6-3 SPECIFIC GRAVITY AND TEMPERATURE FOR SELECTED FUELS (SUTTON & BIBLARZ, 2001)

Despite this, Hydrogen with its low atomic weight and energetic burning means that its performance is usually about 25% greater than other fuels... a substantial performance improvement and making it the preferred chemical fuel for our Saturn VI starship.

Note that there are other fuel/oxidizer combinations that have superior performance to LH/LOX. For instance, using a Fluorine/Oxygen combination (called FLOX) for the oxidizer can yield performance increases in rockets depending on the fuel used and the Fluorine/Oxygen ratio. In the case of one

analysis, using RP-1 as fuel, FLOX 70 (70% Fluorine, 30% Oxygen) led to an impressive 14% increase in performance (Clark, 1972). For anyone that is remotely familiar with Fluorine, it is a difficult product to handle since it will react with almost anything- and is extremely toxic to boot. The minimal advantages to using fluorine are not sufficient to offset its disadvantages.

Finally, let us consider how we will get the LOX and LH to our spacecraft. When considering fuel and oxidizer for our relatively small ship, we would usually just bring them up from the earth. However, there is another option- they can be brought up as dense and relatively easy to handle water. Once in space we could separate them through electrolysis (in a reverse process to that of the fuel cell) to separate them into their LH and LOX constituents. Electrolysis requires a lot of power, but this power can be provided by solar panels that are on our space construction shack.

Using the current, most efficient technique, called PEM or alkaline electrolysis, with an efficiency of 70-80%, one kg of hydrogen requires 50-55 kwh of electricity. A large orbiting Solar Power station of 1 MW can produce about 18kg per hour. This would take us about 245 days to separate our required amount of hydrogen. A 100 MW power plant will make 43,200kg of hydrogen per day and would make all our needed LOX/LH in about 25 days. This is a fairly long time with high-power requirements so bringing the LOX/LH up from earth may be a better option- but in orbit separation of LH/LOX is an option that needs to be considered. The current technology for building a 100MW nuclear plant is immature and the mass associated with lifting our power plant and associated hydrolysis equipment may make water separation not much better than shipping the LH/LOX from earth.

We could also consider a variation of this concept for our storage of fuel. Instead of large LH/LOX tanks, we could have our fuel stored as water with a couple of small tanks for LH and LOX for our engines. We would fill up these tanks with enough fuel and oxidizer to leave the earth's orbit, with the rest of the fuel stored as water. As we coast away from the earth, we would start to continuously make more fuel from our power supply. Perhaps once every five days we would light our engines to burn off the accumulated fuel/oxidizer. This method would eliminate the need for large fuel and oxidizer tanks. We would essentially depart our orbit with a block ice. Again, the large power requirements to separate the water into its constituents mean this option may not be as elegant as we would hope.

Technology- Power- Radioisotope Thermoelectric Generator

In the Saturn VB we reviewed the power supplies that were used during the Apollo and Skylab missions- Fuel Cells and Solar Power. For our Saturn VI we will look at alternate sources of power that are more appropriate for the interstellar mission being considered.

Fuel cells and solar power have substantial limitations, whether it is the bulk of the "fuel" or the need to have sunlight to generate the energy required. There is really only one source of large amounts of power that is compact and can last for decades and perhaps centuries- that is some version of nuclear power. Nuclear power comes in three primary forms:

- Radioisotope driven power supplies- whereby the gradual spontaneous decay of radioactive isotopes creates heat that can be used to either warm equipment or generate electrical power. The heat generated by radioactive decay is predictable, gradually decreasing as the

Radioisotopes break down. The heat generation cannot be shut down or varied. Radioisotope generators have a long history in space and are relatively simple devices with no moving parts. We will consider various alternatives to these devices in the next two chapters.

- Fission is a quite different but related mechanism. Fission is what runs large scale nuclear power plants on earth. Like the Radioisotopes in the previous example, the radioactive elements decay releasing energy. As opposed to the Radioisotopes, this release of energy (neutron particles) causes other atoms to split (fission) which in turn releases more neutrons which further split other atoms, creating more energy in a cascading chain reaction. The reaction is moderated by neutron absorbing control rods that prevent a runaway reaction. As opposed to Radioisotope generators, Fission reactors have to be actively managed, and can increase or decrease their power output. Fission reactors typically have large mechanical generators (usually reciprocating units like a Stirling generator or more often a type of turbine) that convert the tremendous heat generated to mechanical and then electrical power. We will consider Fission power plants in later chapters.
- Fusion. This is the power of the sun. Pretty much the only fuels being considered for fusion are hydrogen or helium. Fusion is tremendously difficult to achieve- it requires both heating the hydrogen to tremendous temperatures and keeping the hydrogen at a relatively high pressure. Because of the very advanced and still unproved ability to generate practical fusion power, we will only consider this at the end of the book.

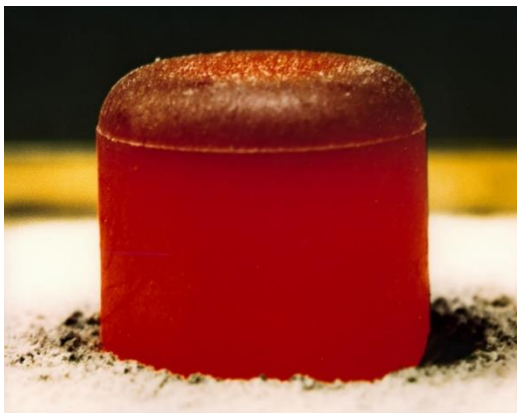


FIGURE 6-4 PLUTONIUM

The only type of nuclear power currently used in space are variations of the first type- so call Radioisotope Thermoelectric generators (RTGs). The most common “fuel” is plutonium. RTGs are remarkable devices- they are compact and extremely reliable with no moving parts and can provide usable power for decades. They derive their power from radioactive fuel and bi-metallic thermocouples. Thermocouples generate power from the Seebeck effect- materials that can generate electrical power across a temperature gradient. In the case of an RTG, they generate power because of the temperature difference between the “hot” plutonium on one side and the cold of space on the other.

Plutonium generates a lot of power per KG of fuel. Plutonium has a half-life of 87.7 years and in practice RTGs have operated for decades with no issues. What does it mean when we say Plutonium has a half-life of 87.7 years? It means is that if the RTG generated 100 Watts at the start of its mission, after 87.7 years it would only generate 50 watts. In another 87.7 years (total of 175.4 years) it would generate only 25 watts.

Because of their simplicity and reliability all interstellar and most deep space probes (as well as many of the Mars Landers) have used this as a power source. Currently the Voyager probes are still active and their RTGs are still generating power nearly 50 years after their launch in 1977.

While RTGs using plutonium can generate power for prolonged periods of time, they are not very efficient. Each of the Voyager spacecraft carried 3 generators, each containing 4.5kg of plutonium. Each generator initially produced about 2400 watts of thermal power- but only about 157 watts of actual usable electrical power. To generate 5000 watts would require 31 generators using 143 kg of plutonium. Newer RTG's are slightly more efficient but not much. The Cassini probe to Saturn had 3 RTGs, each generating about 300 watts of electric power from 7.8kg of Plutonium. Using these RTGs, you would use only 17

generators, and require 130kg of plutonium. Even this quantity of Plutonium is not practical. In the past the United States generated large amounts of plutonium, however this is a major political issue (most reactors that could be used to generate Plutonium are now decommissioned) and will not be quickly resolved- certainly not in time for our proposed Saturn VIB. For many years now the US has produced no plutonium, and we have had to purchase our plutonium from Russia. Currently the US is beginning to make small quantities of plutonium which will slowly ramp up- plans are for the US to produce 1.5kg of plutonium a year by 2023 (Siegel, 2018). Clearly, if RTGs are to play a role, we will have to accelerate our Plutonium production.



FIGURE 6-6 NEW HORIZONS SPACECRAFT

Assuming the spacecraft velocities described in this chapter of 30 kps we would have a mission lasting slightly more than 106,000-years. If we divide 106,000 by the half-life of plutonium, 87.7 years, we get about 1200 generations, each generation producing only half as much power as the prior.

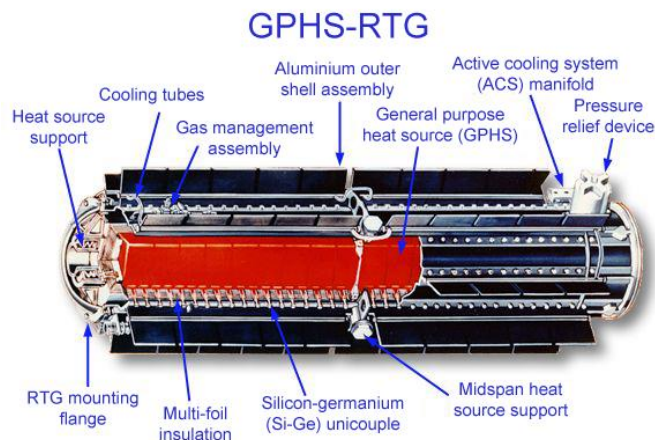


FIGURE 6-5 GPHS-RTG CROSS SECTION

Besides the loss of power due to the half-life of plutonium to a lesser extent there is also the degradation of thermocouples over time. In practice an RTG will have its power drop off a little faster than the half-life of Plutonium. Nonetheless, with no moving parts, no RTG has ever failed in use.

If we were to graph power output vs half-life our curve would look like Figure 6-8. As can be quickly seen power drops off substantially so that by our 6th half-life- we are down to about 1.5% of our initial output.

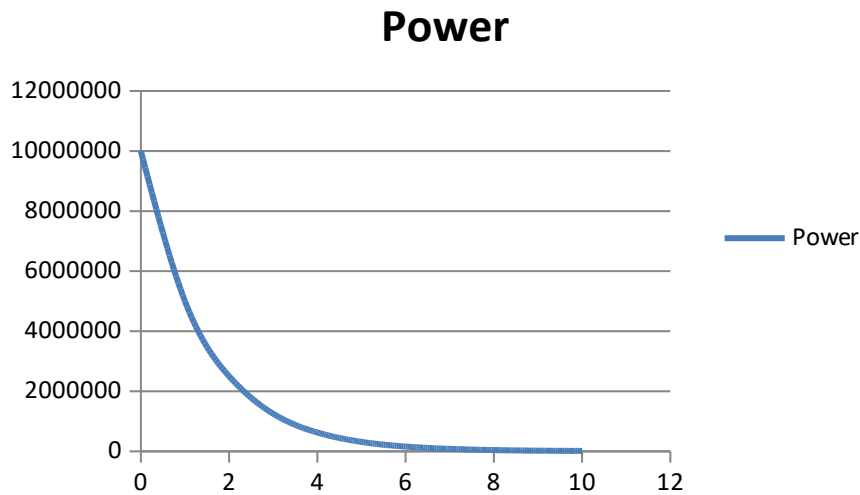


FIGURE 6-7 TYPICAL POWER DEGRADATION OVER HALF LIFE GENERATIONS

At the end of the 106,000-year mission, if we started with 100,000 watts to begin with, we would have essentially zero at the end. Conversely, if we need a very small 1000 watts at the end (to power our probe), each prior generation would have produced twice as much power. Extrapolating backwards, the amount of watts needed at the beginning of the mission would be (literally!) astronomical- about **1.721×10^{361} watts!**

The sun only generates 3.86×10^{26} Watts of power. Indeed, this number is far, far, far more than the amount of energy generated by the whole universe since it was created!

The most power ever generated for an RTG powered spacecraft was for the Cassini spacecraft that orbited Saturn for 13 years. At the beginning of its mission when launched in Oct 1997, its 3 RTGs generated 855 watts of electrical power. By the end of its mission in 2017, because of the natural drop off of radiation from the plutonium, as well as degradation of its thermocouples, its three RTGs put out about 633 watts.

It is easy to understand why people would question the advantages of nuclear power. If nuclear power has so much energy, why do RTGs generate so little power? This is driven by the unfortunate physical reality that using thermocouples to convert the heat gradient of the warm nuclear fuel to the cold of space is not an efficient process- typically they have an efficiency of only 3-7%. The rest of the thermal heat is just waste heat. Because of this, except for a robotic mission, the small amount of usable power generated by an RTG is typically insufficient to supply a manned mission. As noted previously the very small Apollo capsule to the moon had three fuel cells each capable of 1400W (1.4kW). The much larger Skylab produced about 8kw of power on average. The International Space Station generates relatively huge amounts of power from its four solar panel modules- 75-90 kW.

Let us suppose that we used an aggressively low power requirement of 5kw for our mission. Using the power supply used by Cassini, where each of the three RTGs generated an average of 295 watts (at delivery- by the time of launch they had decreased slightly), we would need about 17 RTGs. While this requires a lot of plutonium and would be both expensive and require an expansion of our plutonium supplies, it is also very doable if the desire were sufficient. After only 6 generations of plutonium, or about 530 years, we would be down to only 1.5% of the starting power- or about 75 watts.

How much would 17 RTGs actually mass? While it was noted that each generator had about 7.8kg of plutonium, the overall generator massed about 57kg each. Therefore, for our 17 RTG, the total mass for the power supply would be about 969 kg- or about 1MT. Even though the efficiencies for the RTGs are

low, the power generated by nuclear decay is still substantial and the mass of our power supply would not be an issue for the Saturn VI if it needed to only generate 5kw at the beginning of the mission.

One other point is that 17 RTGs, while giving us 5kw for the start of our mission, would also generate over 70kw of thermal energy. This is a lot of heat and the RTGs would have to be positioned away from our spacecraft on booms so that this large amount of heat does not excessively impinge on either the instrumentation, or crew or on other RTGs. The positive aspect of this thermal heat is that the 5kw of electric power generated is pretty low and by itself may not be sufficient to keep our starship warm... but a portion of the thermal energy could be captured and used for this purpose.

In conclusion, a small RTG powered Starship can generate enough power at the beginning of the mission but will not be a viable energy source for more than a century or two- far too short for our Saturn VI Starship. We do not currently have power supplies that can last for more than a couple of hundred years- or 2 or 3 plutonium half-lives- but in Chapter 7 we will look at possible future alternatives.

Technology- Communications and Raleigh's Criteria

If we send an interstellar probe out, whether manned or unmanned, we will need to communicate back to Earth. What are the challenges for communication over vast distances? Surprisingly large.

Communication to and from a nearby star will require a large amount of power and large transmission and receiving systems. The simplest transmitters like a radio station antenna emit a signal out spherically in all directions, with only a very small amount of the signal actually hitting and being amplified by your radio. This type of transmitter only works if your signal is very strong, and your receiver is very close (tens of kilometers) to work. A more efficient and effective communication system for transmitting billions or trillions of kilometers requires a focused beam. For these systems, transmitting or receiving signals at a particular frequency depends on the power of the transmitter, the size of the transmitting dish or aperture, and the size of the receiving dish.

Most Deep Space probes have large, fixed antennae for beaming information as well as receiving instructions from the earth. The whole spacecraft turns toward the earth to transmit or receive signals. On the earth a large antenna (for the US it is the Deep Space Network) receives the signal and amplifies it. As the spacecraft gets farther away its signal fades as the radio beam gradually spreads out.

All of the interplanetary spacecraft to date functioned on only a few hundred watts of power total. This power is required both to run our instruments and our radio transmitter. Surprisingly, most automated probes do not require much power for their instruments – and it is unlikely that they would ever need more than a couple of hundred watts. The real power drain can be the communications equipment. To send a signal back to earth from 10 light years away will not be easy.

Geometry will show that doubling the distance will reduce the signal strength (I = Intensity) to $\frac{1}{4}$ (see Figure 6-8). Therefore, to keep a signal the same strength if you double the distance, you will need to square the power. There are five things that can be done to reverse this drop off in signal strength:

- Transmit information at a lower speed
- Increase the power of the transmitting antenna

- Increase the size of the transmitting antenna
- Increase the signal frequency
- Increase the size of the receiving antenna

To show how challenging this is, suppose we wanted to use the same size antenna (3.66m) that Voyager spacecraft used to communicate to earth from the distance to Saturn (10 AU). The nearest star as mentioned in Chapter 1 is 268,000 AU- therefore, we want to communicate 26,800 times further than our Voyager spacecraft was. At Saturn Voyager communicated at 44,800 bps (Ludwig & Taylor, 2002, p. 33). That means to keep the same signal strength and using the voyager dish, we would have to use:

$26,800^2 = 718,240,000$ times more power than the Voyager transmitted at.

Voyager had redundant transmitters and amplifiers but the largest was about 29W (Heacock, 1980). To receive a signal of the same strength at earth as the Voyager spacecraft if it were to be 4.3 light years

away would require a transmitter of 20,828,000 watts (20.8 Gigawatts). For our nominal 10 light year mission we would require more than 4 times more power than this!

Needless to say, this is a lot of power.

What are the mitigating solutions?

Transmitting at a lower speed will allow a given signal to be transmitted further due to an increase in the signal to noise strength. However lower rates can only be carried so far.

We can increase the power of our signal. One can easily imagine increasing the power of the antenna by 10 or even 100x. The most advanced deep space vessel launched to date was Cassini. It used a 4m diameter dish with peak power of 53.7 watts (Taylor, Sakamoto, & Wong, 2002)- though it is not quite that simple as

FIGURE 6-8 COMMUNICATION POWER DROP OFF WITH DISTANCE

sometimes several transmitters were operated simultaneously. Regardless, if we increased our power by 10x to a couple of hundred watts this will only increase our effective range the $\sqrt{10}$ or 3.16x.

Next we can increase the diameter of the antenna which has the effect of tightening the beam so that it spreads out less. The beams divergence follows the Raleigh's criterion as stated in the rule:

$$\text{EQUATION 6-1 } \sin\theta = 1.22 \frac{\lambda}{d}$$

Where:

λ = wavelength

$d = \text{diameter of the transmitter}$

Note that since the angle θ is very small so the equation can be simplified to

EQUATION 6-2 $\theta = 1.22 \frac{\lambda}{d}$ (in radians)

Figure 6-9 shows graphically the signal strength vs angle θ . What Equation 6-2 tells us is that the tightness of the beam depends on only two parameters- the diameter of the transmitter and the wavelength of light. The larger the diameter of the transmitter combined with a higher frequency (shorter λ) will increase the signal strength at the receiver by tightening the intensity peak. Note from Figure 6-10 that the wavelength of visible laser light is around 5×10^{-7} meters. If one has the frequency of a radio or light wave, one can easily calculate the wavelength with the formula:

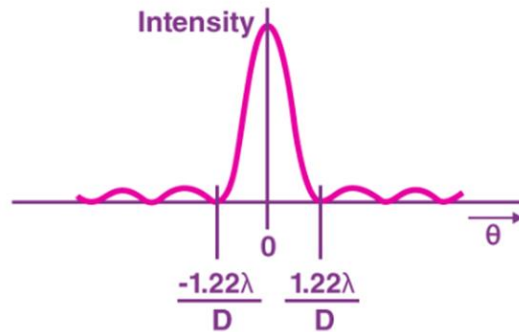


FIGURE 6-9 RAYLEIGH CRITERIA

EQUATION 6-3 $\lambda = \frac{c}{f}$

Where:

$c = \text{speed of light } (3 \times 10^8 \text{ mps})$

$f = \text{frequency (Hz or cycles per second)}$

Because of this physical reality, NASA along with other space agencies are considering using lasers which operate at or near visible light and as such their frequency are much higher than traditional radio waves.

The Cassini spacecraft could transmit at several radio frequencies, but the smallest was the so-called Ka-band which had a wavelength of 1 cm or 30 GHz. As seen in Figure 6-10 light is about 1/10,000 shorter in wavelength hence its frequency is about 10,000 times greater which means

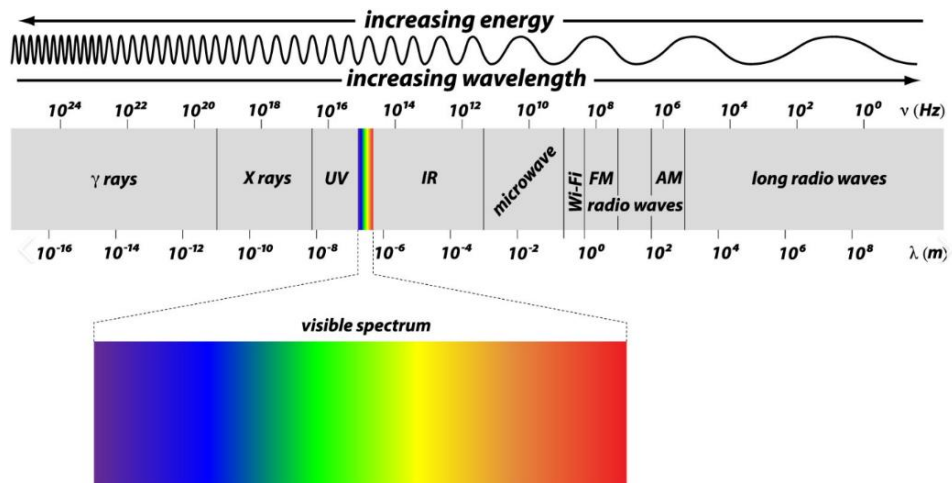


FIGURE 6-10 THE SPECTRUM

our beam will be far tighter for a given aperture. As our distance extends in spacecraft travels out to several light years, it is likely lasers will be the transmitter of choice. In many ways, increasing the frequency is the easiest way to substantially improve performance. Note that since the beam will be so tight, the beam will have to be very accurately pointed, which is another challenge. The movement of the earth around the sun will require that the Starship laser be constantly adjusted to follow its orbit.

The same challenging pointing issue would also exist with the Earth based laser transmitter sending its signal to the spacecraft.

The final way to improve our ability to transmit and receive a signal is to increase the size of the receiver... either a larger antenna in the case of a radio signal, or in the case of laser communications, a larger telescope. A receiver twice as large in diameter will receive a signal four times stronger.

With this knowledge we know that we will likely need to use all five of these techniques to communicate to and from earth- reduce the data rate, increase our transmitter power to thousands of watts, use a larger diameter transmitting antenna or telescope, use a higher frequency (laser) transmitter, and finally make the receiving/transmitting antenna/telescope as large as possible (in the case of a laser transmitter perhaps 10-20m in diameter).

Saturn VIA

To design our Saturn VIA class starship from scratch we will look at the three technology items we have discussed- an LH/LOX engine, powered by RTGs and a laser transmitter.

The higher performance of the LH/LOX rockets can be seen by comparing the exhaust velocity of the Saturn V first stage, powered by RP-1 (kerosene) vs the hydrogen powered engines on the second and third stage where the exhaust velocity is raised from 2.58 km/s to 4.13 km/s. As discussed in Chapter 3, once we fix our mass ratio, the final speed is directly proportional to the exhaust velocity or Specific Impulse. With a MR of 20 the natural log comes out to about three.

Let's imagine a custom designed single stage starship that has a fully loaded mass of 3000mt and a MR of 20. If we assume a LH/LOX engine right from the start what would our performance be?

Final mass (payload and structure): 150,000 kg

Loaded payload and structure mass: 3,000,000 kg

J-2

Engine Weight: 1778 kg

Thrust: 1033 kN

Specific Impulse: 421 seconds; exhaust velocity- 4.13 km/s

Using our rocket equation our final velocity would be about 12.4 kps.

The F-1 engine is 1960's technology. The Space Shuttle Main Engines (also called the RS-25) did slightly better.

SSME (RS-25)

Weight: 3177kg

Thrust: 2278kN

Specific Impulse: 453 sec; exhaust velocity 4.436 km Sec

Our final velocity would equal about 13.29 kps. This is substantially faster than our Saturn VA and VB- about 30% and is also faster than our Starship. Even with the higher tech SSME you can't change the laws of physics so even though it is an improvement over the Saturn V, it would clearly not be fast enough for a starship.

On a more practical level, which engine, the F-1 or the RS-25, is better? One negative with using the SSME over the F-1 is that the engine is twice as heavy. It does provide twice as much thrust, and since it was designed to be reused it should be more reliable and operate longer. During the Shuttle Program the engines were estimated to be good for 30 starts and 15,000 seconds of operation (Jenkins, 2012). These starts, and total operation time assumed that maintenance would be performed in between each start. Keep in mind that until engines started getting reused (Shuttle, Falcon 9) they only had to operate for a few minutes and then were thrown away so a continuously firing or frequently started engine is a relatively recent invention. Both the F-1 and the SSME are relatively old designs... the F-1 from the 1960's and the SSME primarily from the 70's and 80's. When the SSME was first developed it operated at a chamber pressure of 2994psi (Aerojet Rocketdyne, n.d.)- or 20.64MPa (200.64bar). This was high for the 1980's. The new Raptor Engines on the SpaceX Starship operate at 300 bar (Everyday Astronaut, 2022) or 30MPa so it is likely that the SSME performance may be able to be raised with a slightly higher specific impulse. All things being equal, higher pressure will lead to higher exhaust velocity and possible reduced mass since we can have the same thrust but be in a smaller chamber. The SSME engine is a very good engine with high performance but can be further improved in reliability, as well as improving its performance with an increased impulse, thrust and a reduction in mass. Going forward we will specify an improved RS-25 called RS-25+ that will have a nozzle designed to operate purely in a vacuum and with a specific impulse of 460. With this performance we could achieve a final velocity of about 13.52kps.

A single RS-25 uses about 514 kg of fuel and Oxidizer per second. To go through our 2,850,000 kg of propellant/oxidizer operating at full throttle will take about 92 minutes. The engines did not operate at full throttle during the entire shuttle launch and our rocket probably would not either. Nevertheless, this points to a concern I would have with counting on a single engine... it is doubtful that the RS-25 could operate this long continuously without failing, even if operated at a reduced thrust. Nonetheless, since the RS-25 was designed to operate for 15000 seconds with periodic maintenance during this time I believe we have a sound basic engine that can be further improved to increase its endurance.

If we launched at exactly the right time in our orbit to take advantage of both the 8 kps orbital velocity, our escape velocity from Earth would be approximately:

$$v_{\infty}^2 = V^2 - v_e^2 = (13.52 + 8)^2 - 11.18^2 = \sqrt{338} = 18.4\text{kps}$$

If we took advantage of our 30 kps velocity around the sun our escape velocity from the solar system could theoretically be.

$$v_{\infty}^2 = V^2 - v_e^2 = (18.4 + 30)^2 - 42^2 = \sqrt{577} = 24\text{kps}$$

This is a great escape velocity but to reiterate a point made several times already, it is not very useful as it would be strictly limited to the plane of the ecliptic. A more realistic number if headed out of the ecliptic would likely be less than 20kps.

At the beginning of this chapter, we mentioned that we would also attempt to build a rocket that was both faster and could keep its crew alive longer. To determine how many supplies could be carried we need to see how massive our rocket structure would be.

Building a large rocket of 3million kg whose payload is 150,000 kg is well within engineering capabilities if operating in a low g environment. Many rockets (including our original baseline Saturn V) achieve this or even greater performance with staging but this is because of the issues associated with operating engines at different altitudes, aerodynamic stresses, high g loads etc. If designed to operate strictly in the low g vacuum of space the rocket can be structurally a lot lighter. Because of this, with our Saturn VIA we will consider no staging. In the weightlessness and vacuum of space, the forces and stress on our rocket are much less and our rocket engine(s) does not need to be optimized for different heights but for a vacuum only. Since we are not launching a rocket from the ground within the earth's deep gravitational well, we can reduce our spaceship to a single engine and eliminate the massive 5 F-1 and J-2 engines of the Saturn V- along with their associated pumps and hardware.

Our Saturn VI will consist of a 150 metric ton structure and payload holding 2,850,000 kg of LOX and H₂O. We may need to build either two large tanks for the LH and LOX but depending on the specific design we may make our Starship modular and put up several smaller tanks- tanks that can be fabricated on earth and be lifted into space as payload. Regardless the tanks will not need to be very strong as they will not be operated on earth or in our atmosphere so will not have to handle the structural and aerodynamic stresses of tanks that are launched from earth. They will need to have considerable insulation so that when they are filled our liquid hydrogen and Oxygen do not boil away.

Using the SS External tank as a guide let us design our starship LH and LOX tanks. During the several decades of SS flight the External Tank was redesigned several times to reduce its weight. For the first seven missions the empty tank was 35,000kg or more. Several iterations followed which progressively reduced the tank's weight. In the late 1990's NASA was using what was called the Super Lightweight tank whose empty mass had been reduced to 26,500kg. The SS loaded fuel tank weighed 760,000kg. This meant that the total fuel and oxidizer mass was 733,500kg.

For the Saturn VI we are looking at 2,850,000 kg of fuel- or 3.87x as much. Assuming a tank of the same diameter our volume and surface area will go up linearly and we can do some quick approximations. The SS main tank was about 8.4m in diameter and 46.9m long. Assuming we kept the diameter the same, we

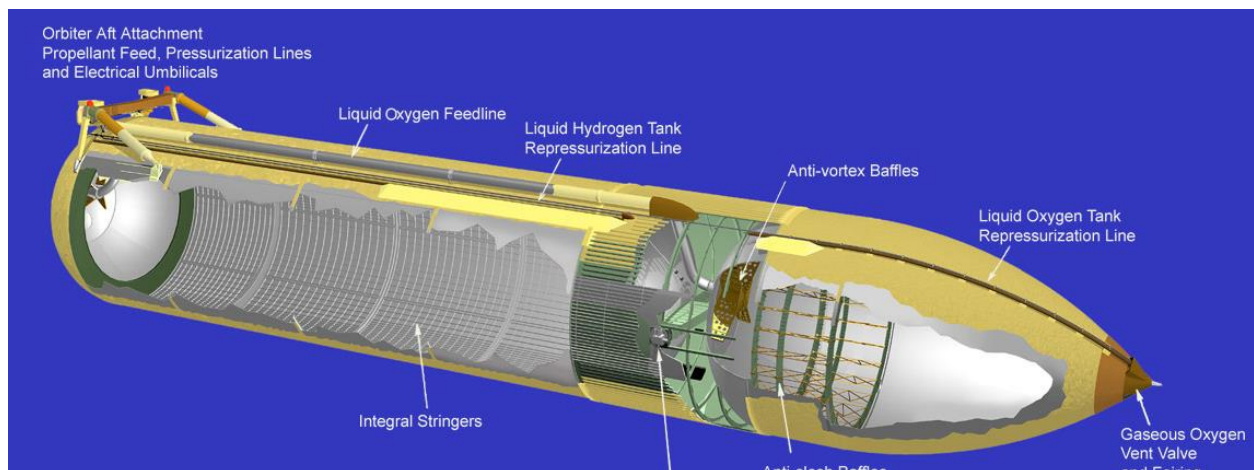


FIGURE 6-11 SPACE SHUTTLE EXTERNAL TANK (COURTESY NASA)

would have a tank 3.87x longer and (simplifying) 3.87x heavier at 103,350kg. This would leave us only 46,650kg for our power, rocket engine, habitation module and supplies. In reality the SS ET were two separate tanks joined together by an intertank which, besides serving as streamlining, also served to carry the loads of from the Solid Rocket Boosters. In addition, the top tank (Oxygen) was streamlined for travel through the atmosphere. By elimination of the streamlining and the intertank, along with a reduction in strength since you don't have the large thrust and aerodynamic loads on our starship means you could reduce the weight further. In Table 6-3 I calculate the weight of the tank based on surface area. Using our 26500kg empty weight and calculating a theoretical surface area for a hydrogen and oxygen tank cylinder, I come up with 22kg per m². For a structure that will only be used in space, I figure we can lower some of the mass by at least 20% to about 17.5kg per m².

To keep the hydrogen and oxygen (but particularly the hydrogen) liquid mean that there would still be need for substantial insulation to these tanks. Furthermore, while the stresses from launching and traveling through the atmosphere were eliminated, permitting us to lighten the tanks some, the reality is that the shuttle LH tanks were pressurized to about 30 psi (about 202 kPa) so to maintain structural integrity you are still required to design a fairly robust tank.



FIGURE 6-12 SPACE LAUNCH SYSTEM (SLS) WITH 8.4M DIAMETER TANK (COURTESY NASA)

If we were to calculate the relative sizes of the two tanks (Hydrogen and Oxygen) we can use the same fuel/oxidizer ratios since we are using the similar engines to what was used on the SS.

Hydrogen accounted for about 106 MT of mass, and oxygen about 630MT. One thing that becomes immediately obvious is that liquid hydrogen is far less dense than liquid oxygen. With the SS the mass of the oxygen was over 6 times more than the hydrogen, even though the hydrogen tank was almost 3 times larger. Liquid hydrogen has a density of 70.85kg/m³ whereas liquid oxygen is about 1141kg/m³. These are approximate numbers-if you lower the temperatures below where LH and LOX liquify, they will continue to increase in density per Figure 6-3.

Note also that oxygen, per molecule, is eight times heavier than the two hydrogen atoms that it combines with when burning... but the SSME has only 6x the mass of oxygen to hydrogen. This is because the SSME engine burns fuel rich (more hydrogen than oxygen). Indeed, most engines run fuel rich because this increases the nozzle efficiencies (the lighter unburned hydrogen would travel faster than the unburned oxygen in the case of an oxygen rich burn) and the

unburned hydrogen will permit the engine to run cooler.

The Space Launch System currently being designed uses a similar but slightly larger version of the SS External tank. Its empty weight is surprisingly proportionally heavier than the SSs... 85,275kg. Part of this

is because it carries more fuel/oxidizer and is therefore a longer tank- while maintaining the same diameter. It is about 64.6m long. Besides being longer than the ET, I suspect the increased mass is driven by the fact that the second stage and payload are mounted on top of this stage- there is no SS strapped to the sides and all loads are carried by this tank including the four SSME mounted at its base.

For now, we will assume we could fabricate a tank that masses 17.5kg/m²? How heavy would these tanks be?

In the first case we can eliminate the tank streamlining and assume the optimum case that the tanks were perfect cylinder to calculate how large our tanks would need to be.

The volume of a cylinder is:

EQUATION 6-4 $v_c = \pi r^2 h$

For a fixed radius, to calculate the height we rearrange the terms:

EQUATION 6-5 $h = \frac{v_e}{\pi r^2}$

The area of a cylinder is:

EQUATION 6-6 $a_c = 2\pi r(r + h)$

Rearranging to calculate h

EQUATION 6-7 $h = \frac{a_c - (2\pi r^2)}{2\pi r}$

We also will consider using spherical tanks. The Volume of a sphere is:

EQUATION 6-8 $v_{sphere} = \frac{4}{3}\pi r^3$

And the surface area is:

EQUATION 6-9 $A_{sphere} = 4\pi r^2$

Calculating various surface areas and masses using our 17.5kg/m² structure mass we come up with the following empty tank specifications:

Cylindrical Tank Saturn VIA	Theoretical Shuttle Hydrogen Tank	Theoretical Shuttle Oxygen Tank	Theoretical ET Total	Theoretical SLS Main Tank Hydrogen	Theoretical SLS Main Tank Oxygen	Theoretical SLS Total	Saturn VIA Hydrogen Tank	Saturn VIA Oxygen Tank	Saturn VIA Total
Mass (MT)	106	629	736	142	844	988	415	2468	2883
Vol m ³	1497	553	2075	2000	742	2742	5860	2170	8030

Length (8.4m diameter)	27.3	10.1	37.4	36.1	13.4	49.5	105.7	39.2	144.9
Surface Area	831	377	1208	1063	464	1527	2900	1145	4045
Actual designed weight			26,500			85,275			
Proposed Weight (assume 17.5 kg per m ²)			18,603			26,723			70,788
Spherical Tank Saturn VIB									
Diameter	14.25	10.23		15.63	11.23		22.37	16.06	
Surface Area	638	329		767	396		1572	810	2382
Weight (assume 17.5 kg per m ²)	11,165	5,758	16,993	13,423	6,930	20,353	27,510	14,175	41,685

TABLE 6-3 EXTERNAL TANK CONFIGURATIONS

These calculated cylindrical lengths are the minimum, as the assume a perfect cylinder with flat ends. In reality, both the LH and LOX tanks are under pressure, and for structural strength and to eliminate excessive corner stress, the ends would be curved into a dome like configuration which would cause the real tanks to be slightly longer and more massive. In the table we calculated the SS total tank length at 37.4m. How does the compare to the real mass and dimensions on the shuttle External Tank? As mentioned, the latest version of the SS ET massed 26,500kg. The ET hydrogen tank was about 29.6m long and 16.6m for Oxygen and had a total length of 46.9m. The hydrogen tank calculation is close to this. The extra length for the Oxygen calculated length is undoubtedly due to the aerodynamic shape including the large intertank that separates the LOX from the LH.

We can come to a couple of conclusions from this table. For one, our tank weight can easily be under our m1 mass of 150,000kg. In order to minimize the mass, the best configuration is spherical. In theory the stress on the spherical tank will be greater requiring a slightly thicker shell but the surface area is only about 60% that of a cylindrical configuration. With that being said, building a spherical tank in orbit is a major endeavor that currently is beyond anything done in space to date.

Also, the assumption is that the material used is similar to that used on the SS External Tank. Later on, we will be looking at building a habitation torus made of aluminum alloy with a density of 2700kg per

m². To give an idea of how thick these fuel tanks would be, using this number for aluminum our SS ET and our original calculation of 22kg per m², our structural thickness works out to be .008m thick (about 8mm). Using my proposed zero gravity optimized weight of 17.5kg per m² our structural thickness works out to be about 6.5mm.

There are more robust and accurate methods for estimating our tank mass that we will look at in later chapters. Besides the shape of the tank (cylinder, sphere) the size of the tank and the pressure the fuel/oxidizer is stored at will all determine the required wall thickness. On the SS ET the LOX tank was pressurized to 150kPa and the LH tank to 202kPa. As the tanks get larger, the cumulative stress of this internal pressure becomes substantial and requires thicker skin. For now, with tanks only a few times larger than the SS ET, our estimate should suffice.

One thing that we have not considered is that it is tough to keep hydrogen in liquid form as it tends to boil off very quickly. The SS was fueled with hydrogen only minutes before lift-off because even though its External Tank was insulated, it is very tough to keep the hydrogen to below 4K... as the Shuttle waited for lift-off hydrogen would continuously vent. For our “deep space” vehicle, we will need to keep our tanks cold for a prolonged period of time as it is unlikely that we could continuously load the fuel and launch as quickly as the Shuttle was done. In addition, because we have only one engine and over 3 ½x as much fuel our one engine will run for almost an hour and a half vs the typical 8 minutes for the Shuttle.

We have one final (at least for our purposes) item to consider. How will these tanks be made? Most orbital rockets can handle payloads 5 meters in diameter. Some of the proposed rockets can handle larger payloads- Blue Origins New Glenn should be able to handle a 7m diameter. The largest currently planned payload carrier is the SpaceX Starship, and this may be able to carry an 8.4m diameter tank section. Simpler still, we might just launch a modified version of the SLS where, without a payload and second stage, the rocket performance looks to be enough to have its empty tank reach orbit. We could then (with some in orbit construction and modification) attach several of these tanks together to give us our required volume. The most efficient configuration, but the hardest to make, is the spherical tank which besides being lighter will also be easier to keep the LH and LOX cool (because of the reduced surface area).

To summarize our options to get our spacecraft to low earth orbit.

- We can assemble the whole tank and payload on earth and launch it into space. This would have to be done by launching many rockets from earth since a single rocket with the ability to launch a 3000mt payload is far greater than any rocket currently being designed. A single rocket with our 3000mt Saturn VI as its payload, would have a total launch weight of at least 30,000mt- 60,000mt for a multistage rocket. This is 10-20 times larger than anything ever built. The acoustic effects of the rocket engines on liftoff would likely be so destructive that windows would be shattered for kilometers around. Finally, the sheer dimensional size of the starship, primarily its fuel tanks, are far beyond the capacity of any planned rocket.
- We can assemble it in space with a space-based manufacturing plant out of millions of components. This would likely be the most weight efficient method- i.e., the tank structure could be spherical and the lightest thereby allowing for more of our useable payload. However, we have never done welding in a vacuum under conditions of zero gravity. We have assembled some large spacecraft (mainly the ISS) from premade modular components, so we do have some

practice in space assembly. Large-scale welding procedures and equipment would have to be developed and would likely be difficult to carry out, especially in the short term (next 20 years). Long term this will be a skill that will be needed so the techniques developed can apply to the more advanced starship projects.

- We can fabricate the major assemblies (both payload and tanks) on earth and assemble and bolt or weld them together in space. The amount of welding would be kept to a minimum.

In the near term, Option 2 looks to be too difficult so we would go with Option 3. Using the SpaceX Starship 9m in diameter cargo bay or the SLS to get our tanks into space we would launch cylindrical tanks (with a diameter of 8.4m) into orbit and then weld the tanks together end to end until we got our required volume. Also, because of the rounded end caps of the oxygen and hydrogen tanks, and the fact that the two tanks would not be flush against each other, the actual full length of the tanks would likely be closer to 160m.

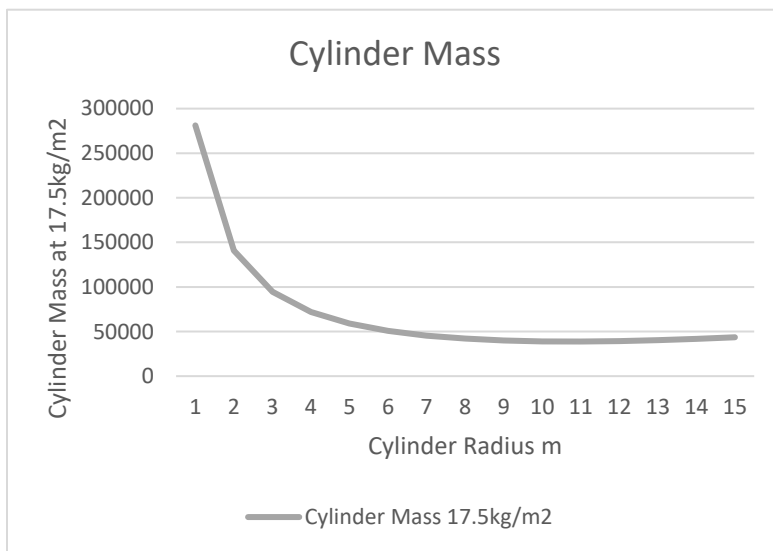


FIGURE 6-13 MASS OF VARIOUS CYLINDERS OF 8030 M³ VOLUME

more weight efficient than the pre-made cylindrical tanks by permitting diameters larger than 8.4m. Graph 6-4 shows the weight savings because of the smaller surface area as we develop larger diameter cylindrical tanks. You can continue to lighten the tanks up until the cylinder height equals the diameter. This is a simplification as, like the spherical tank, the stress on a larger diameter cylinder will increase necessitating a thicker structure and offsetting some of the weight savings. The overall point is that, for a particular volume, a greater diameter cylinder is more efficient for holding large quantities of fuel or oxygen (up to a point) than a small diameter cylinder.

Regardless of the path chosen, some welding and assembly will be needed which will require us to build a construction shack to help assemble the Saturn VI components.

Finally, let's determine how much acceleration stress will be on our starship? Using our starting mass of 3 million kg and our thrust of 2,279,000 N from our single SSME we can easily calculate our initial acceleration:

EQUATION 6-10 $F = ma$

Since we are required to weld the cylinders together, we may even consider a different approach. If the in-orbit welding technology advances enough over the next couple of decades, it may be best to just send up aluminum sheets and bend them into hoops and weld the two ends together. Once the hoops are assembled, we could then weld these cylinder hoops together to make a longer cylinder. This will be more complicated than the pre-made cylindrical tanks, but less complicated than constructing a spherical tank. Critically it would be

EQUATION 6-11 $a = \frac{F}{m}$

$$a = \frac{2,279,000}{3,000,000} = .76 \text{ mps}$$

or less than 1/10th of a g.

Of course, as the rocket consumes its fuel and oxygen, it will start to accelerate and its g force will increase, but the rocket will also have much less stress from the mass of the fuel. At rockets burnout the g force would be 15mps or about 1.5g. To make matters even more manageable, the SSME engines were also throttleable down to 67% so our acceleration could be kept to a maximum of about 1g.

For our final summary, we will use an empty weight of around 41,685 kg based on tanks that 8.4m in diameter but are 3.87x larger than that of the SS and 20% lighter per m² of surface area. This leaves over 108mt available for payload.

The numbers are what they are- the rocket equation is inflexible- mass ratio and exhaust velocity determine your rocket's performance. Are there any other techniques that can help improve our performance?

Launching from the Lagrangian point

One of the first things we could consider is to build the spacecraft away from the earth's gravitational field. There are several, relatively stable areas around all large planetary bodies called Lagrange points.

These points were described in paper in 1772 by Joseph-Louis Lagrange titled "Essay on the three body problem". A spacecraft built at one of these points would stay in that position. Normally the positions most considered are the so-called L3 and L4 positions. If a spaceship were being assembled there, it would maintain a relatively constant distance from the earth and sun but would be far enough away from the earth that earth gravity would not be relevant- so there would be no gravity losses from leaving the earth. As mentioned in Chapter 1, the earth itself moves around the sun so already has an impressive velocity of 29.8 km/s to stay in its orbit.

If we had our starship built at one of the Lagrangian points, we would be still orbiting the sun at the same speed as the earth and we could take advantage of this velocity and use this orbital speed around the sun. If we ignite the rocket when it is pointing perpendicular to the sun in the direction of its orbital motion, we will gain this speed. As before, if we go in any other direction other than the direction that which the spacecraft orbit is headed, we will lose much of this velocity boost.

As a spacecraft leaves the sun it drops off in speed as it climbs the gravitational well. You can see this effect on the Voyager flight profile in Figure 2-8. If you look closely, the Voyager spacecraft drops speed rapidly when leaving the earth and then the sun. Some of the velocity loss occurs as the spacecraft

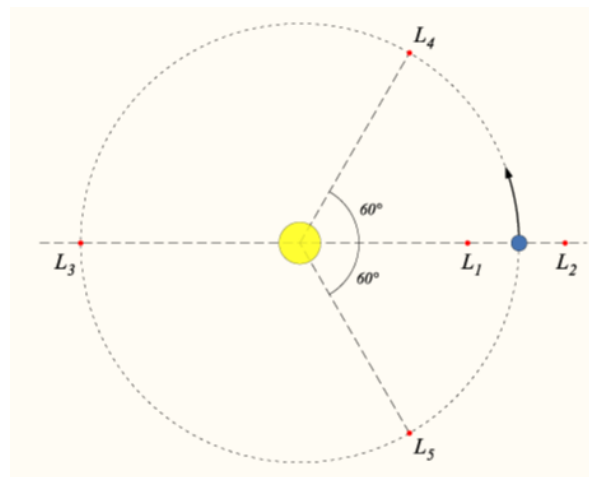


FIGURE 6-14 LAGRANGE POINTS

climbs out of the earth's gravitational well, and then out of the sun's gravitational well. By building the starship at the Lagrange point you would eliminate the losses from leaving the earth- and your curve would more closely follow the blue escape velocity line. This is not as much of an improvement as you would imagine. This is because if we built are Starship in Earth's orbit you would already have a lot of speed around the planet- around 8kps. In theory, combining the velocity of an object in orbit around the earth (8kps) with the earth's orbital velocity of 29kps you are already traveling at 37kps. If we added our Saturn VI spacecraft velocity of 13.5kps you would be traveling at 50.5kps. However, the earth's gravity and even more importantly, the sun's gravity will quickly slow you down and building at the Lagrangian points will not help you with the sun's gravitational losses, while simultaneously denying you the 8kps satellite orbital velocity around the earth.

Furthermore, orbiting at L3 or L4 also means you may have to wait weeks or months for supplies. Because of this I don't see any compelling reason to construct our spaceship at one of these points.

Gravitational Slingshot

As we see, our Saturn VIA is severely limited in its capabilities. While its payload is impressive, and we can reach a solar system exit velocity as long as we are in the direction of the ecliptic, our chemical engines are just not energetic enough to get to a very high velocity, nor go to most of the desirable stars since they are not close to the ecliptic. There is however another trick we have up our sleeve that can impart a sizeable velocity increment to our rocket- the gravitational slingshot mentioned in Chapter 2. This technique has been used for all spacecraft that humans have sent into interstellar space.

As discussed, using Jupiter for our gravitational slingshot can optimally get a little more than a 10kps boost in speed. Alternatively, we can use Jupiter's large gravitational field to deflect our spacecraft out of the ecliptic, though this may negate most or all of the slingshot velocity boost. If launched close to the ecliptic from orbit around the earth, we could be traveling as fast as 24kps before using the slingshot. If we leverage a Jupiter gravitational slingshot, we may gain a little over 10kps, though considerably less if we are headed to a star off the ecliptic. Optimally we may have an exit velocity in excess of 30kps- though more realistically for a typical star our final speed may be closer to 25kps.

Tank Material Selection

We have selected some sort of aluminum alloy to make our fuel tanks since this is what the SS and SLS use but other materials may be considered including steel, titanium, and composites. Since aluminum has been successfully used in most rockets, and meets our mass requirements, it is probably a good choice. Depending on the ease of welding in space, other materials may turn out to be better. Further engineering development will be required.

Unmanned

As can be seen in Appendix C robotic probes typically have small payloads. Cassini, the spacecraft that orbited Saturn for almost a decade had a science payload of less than 1000kg. Based on the capabilities of electronics it would not be unreasonable to assume that even an interstellar spacecraft with a robust suite of telescopes and imagers, as well as a powerful communications device would mass no more than 10,000 kg. Furthermore, the instrument suites usually require only a hundred watts or so of power to operate- the largest power demand would likely be the transmitter as described previously. Most of our payload mass could be dedicated to our power supply and fuel tanks/structure.

Manned

The Saturn V launched Skylab had no recycling capabilities. More modern, long duration manned spacecraft do have some limited capabilities. For a multidecade spacecraft, it is necessary to have at least some recycling for the most important consumable resource- water. If we assume a 93.5% water recovery efficiency (as achieved on the ISS) (Doty & Garcia, 2021) and we use 4664 liters per year for a crew of three, at 93.5% recycling efficiency we would lose about 303 liters of water per year.

We would also lose some oxygen. Indeed, all waste generated, either directly from the astronauts or their emptied food containers would be periodically ejected from the spacecraft. Each time something is ejected a portion of your water and oxygen would be lost. It is hard to tell how much - it depends on how effective your pumps are in removing the atmosphere from your disposal unit before being ejected. Regardless, oxygen can be easily generated via electrolysis from water, but this also increases your water usage.

How much oxygen is lost and would need to be replaced? A very tight spacecraft would lose very little- in theory a sealed metallic spacecraft would lose nothing. Most of the losses would be from opening to spacecraft hatches for spacewalks, waste being ejected, and how tight your hatch seals are. The ISS generates between 2.3kg and 9kg of oxygen per day (O'Callaghan & Kremer, 2012). I assume that it needs to generate this much to replace that which is lost for various reasons. However, the ISS is much bigger than our Starship Skylab derivative, consisting of many modules attached together, frequently 6 or more astronauts, and who perform space walks every few months if not more. I would think the lower value of 2.3 kg per day would be an appropriate target. Since water, by mass is about 88% oxygen, we arrive at a consumption rate of water for oxygen generation of 2.6 kg per day. This would NOT be recycled.

Using these quick approximations, an annual water loss of 303 liters (or 303kg), plus an additional 750kg used to generate replacement oxygen, we would lose about 1053 Kg per year or 21,060 kg over 20 Years.

For Food, the situation is about the same. Even dehydrated food has mass- in Chapter 5 we used the number of 1.77kg of dry food per day per astronaut. Assuming we add water into the food, what is a reasonable weight of food at the beginning of the mission? It depends on how aggressive and how bland and unappetizing we are prepared to make our food. For now, we will stick with our 1.77kg per day- which works out to about 1940 kg per year for 3 astronauts. For a 20-year mission we would start off with 38760 kg of food. Note that if the spacecraft is large enough, and has enough power, food could be

grown which would reduce this usage- waste food could be recycled into the new crops. We will consider these options in later chapters. For now, for our Saturn VI we will only try to recycle the water. Using these assumptions, we will go through about 2990kg per year of total consumables.

In Chapter 5 we also assumed a slightly smaller and customized designed habitation module that was 40,000kg. This could be partly achieved by making a ship with only 300m³ of habitable space- far more than Apollo but far less than Skylab.

How long would our supplies last for a crew of three given these parameters? Per Table 6-4 a Saturn VIA would have enough supplies for a crew of three for 19 years.

Our spacecraft mass would break down as follows:

Item	Mass (MT)	Comments
Fuel (at mission start)	2,850	LH/LOX propulsion
Empty tank(s)	42	
Power Supply (5kw)	1	17 RTGs; 5000W
Engines	5	1 SSME equivalent engine
Structure	45	Habitation Module (40mt) and associated hardware, booms, antenna (5mt)
Payload	57	19 years- a crew of three, using 2990kg of water, food, and consumables per year.
Total	3000	

TABLE 6-4 SATURN VIB (SPHERICAL TANKS)

Cost

As opposed to the somewhat absurd design of the Saturn V starship which was never designed to be disassembled and reassembled in orbit, with the Saturn VI we can begin developing approximate costs. No new technologies are needed other than the ability to weld in space. The modular assembly techniques have already been demonstrated on various other space projects including the ISS. Nevertheless, some space-based manufacturing capabilities would be needed, and it is likely a small manufacturing facility would need to be built in orbit. The exception to this would be using a SpaceX Starship which would require redesign on earth to increase its mass fraction but is already being designed to be refueled in space. Besides the small manufacturing facility, since we are essentially using an engine already designed, the main structural item to be designed are the large tanks.

As space travel becomes more prevalent, I would anticipate some further decreases in launch costs from the current Falcon 9. I believe a reasonable cost using the SpaceX Starship of \$50 million for 100 mt per launch would give us a cost of about \$500 per kg- or about ¼ of what SpaceX costs currently are. Launching the Saturn VIA 3000 mt rocket (primarily fuel or water which will be separated into LH and LOX) to orbit would require a minimum of 30 launches. We would also need to build a small manufacturing facility to both help fabricate our rocket as well as to generate hydrogen and oxygen if necessary. The manufacturing facility would likely have a mass almost as large as our fully fueled Starship and would require a couple of dozen flights combined with resupply missions to bring crew up and back along with their stores and supplies. I could foresee a minimum of 200 flights to build and fuel our starship, build and supply the manufacturing facility, and provide all the consumables and supplies needed during the construction.

With so many unknowns it is hard to develop a reasonable cost estimate but for real rough order of magnitude:

Saturn VIA Activity	Cost (Billion \$)	Comments
Design Saturn VIA Starship	\$3	Rocket Component Design including tank, , upgraded RS-25+ engine
Construction of Saturn VIA Rocket	\$3	Component Construction Costs on Earth
Payload Design and Construction	\$4	Design of Water Separation system, Habitation Module, Communication, Power
Payload Construction	\$1	Habitation Module Construction
Launch Costs	\$10	200 launches, 100mt per launch; \$50million per launch; 30 Launches for Saturn VIA components, 170 launches for support and construction materials
Design of Space Manufacturing Station	\$3	
Construction of Space Manufacturing Station	\$4	Mostly Component Construction on Earth
Research and Development of key space manufacturing technologies	\$1	Welding
Construction Costs in Orbit	\$1	Personnel; equipment; supplies
Total	\$30	

TABLE 6-5 COST FOR SATURN VIA

These numbers are notional and really crude but are to give an order or magnitude approximation. It assumes a motivated team and a streamlined development program with little or no traditional government involvement as well as minimally modified “off the shelf” components.

Summary and Conclusions

With our Saturn VI we attempted to build a dedicated starship. We picked the best, most energetic chemical rocket engine in existence. We also engineered a modular design that would be possible to launch from earth.

Our custom designed starship can achieve a velocity of about 13kps. At the earth- sun distance the escape velocity from the sun is 42 kps. Taking advantage of the nearly 30 kps earth orbital velocity around the sun and the 8 kps orbital velocity of our starship around the earth, it is possible to see an escape velocity of about 20kps. With a gravitational boost from Jupiter, we may leave the sun with a velocity with a final velocity of 30 kps, but more realistically we will probably use Jupiter to divert our spacecraft out of the elliptic and little or no gain in speed would occur. Historically even with gravitational slingshot- or perhaps multiple slingshot's, it is difficult to escape the sun with chemical rockets much above 20 km/s. Voyager 2, while not specifically designed to exit the solar system at a maximum speed, did exit at about 15km/s but only after using a slingshot from 4 planets (Jupiter, Saturn, Uranus, and Neptune). This kind of alignment is very rare (about once every 179 years). Our Starship, with its energetic Chemical fuel combo, and high mass ratio will comfortably exceed Voyagers' performance and could likely be on the order of 25kps. This would get us to about 10 LY in 120,000 years. This extremely long mission combined with the inadequate power options, the payload would be inert within at best, a few decades after launch. Using our rough rate of consumables, RTGs for power, and water recycling of 93.5% we could send a crew out for about 19 years- an impressive feat but only about 1/6315th of the requirement.

The reality is that chemical reactions, of which hydrogen and oxygen is on balance the best, do not have enough energy to create specific impulses much higher than what we have considered for the Saturn VI. Before we go on to more energetic fuels let's extrapolate and see how far we could push a chemical rocket's performance by drastically raising the mass ratio. Remember in chapter 2 we looked at a rocket whose final velocity was 20x its exhaust velocity. This rocket had a mass ratio of 485 million to one. This would seemingly be an impossible goal but using some creativity we may be able to build such a rocket.

In the inner part of the Solar System, primarily between Mars and Jupiter, lies the Asteroid Belt. The asteroid belt is made of millions of objects ranging in size from Ceres at 952km to small boulders that were blasted off of larger Asteroids that got hit by other Asteroids. The Asteroids are mostly rock, silica and metals. Further out at the edge of the solar system are even more objects in what is called the Kuiper Belt. Even further out, is the Oort cloud. The Oort cloud in particular is filled with billions of objects ranging from objects smaller than a meter to objects thousands of kilometers across. The Oort cloud is ultimately the source of all comets we see. Many of these objects have a large percentage of water- indeed many are mostly water by mass.

Suppose we landed a nuclear reactor on one of these water rich objects. The reactors' power would be used to first melt some ice, then separate the water and hydrogen through the straightforward process of electrolysis. Electrolysis is somewhat slow with a small reactor but over the course of a day or days you would gradually fill up a couple of tanks with Oxygen and Hydrogen. Once you had sufficient quantity you would use them to fire a LH/LOX single long duration rocket engine anchored to the body. You may only have enough fuel to run the engine for 10 or 20 minutes and then would shut down. Then

you would start the whole process again, separating the water into its components, filling the tanks, then lighting the engine. You would likely do this process thousands of times spread over many decades or even centuries. The entire minor planet would be the storage tank- in other words you eventually burn up all of this huge mass, and the only part left when you were done would be a small payload, a nuclear reactor, an electrolysis plant, and the small hydrogen and oxygen tanks.

In this way you would have a rocket with a huge mass ratio. In our example in Chapter 2, using our LH/LOX engine with an Isp of 453 which converts to 4,513 mps. Since we decided our target speed is 20x the exhaust velocity this rocket would achieve a speed of 90,252 mps or 90kps.

If we assumed our final mass (payload, reactor, empty storage tanks etc.) were 150 MT how heavy would our initial starting mass be? Remember that to get to a final velocity 20x more than the exhaust velocity we would have a final mass of 1kg with a starting mass of 485 million kg. Now we are saying our final mass is 150,000x more so our starting mass will be 150,000 bigger also. Our starting mass works out to 7.275×10^{13} kg or 7.275×10^{10} MT. While this may seem massive on human scales there are millions of objects in the Kuiper Belt, Asteroid Belt and Oort Cloud that are even more massive. With an Oort object made primarily of water the diameter would be about 5km. This would be an impressive starship but even at 90kps, the time required to travel our 10 light years is 35,000 years, far beyond what is desirable! Nevertheless, this shows that with creative means, even a chemical rocket could achieve a sizeable velocity performance.

It should also be kept in mind that these theorhetical numbers are for an object that is outside the sun's gravitational influence. In reality, our large diameter and massive object we be in orbit around the sun and it would be difficult to move outside the suns gravitational field... if a rocket were placed on a Oort Cloud object and its engines fired, it would slowly spiral out until after many years (likely centuries) its velocity would exceed the sun's escape velocity. These gravity losses would mean that in reality its performance would be far less than 90kps.

Moving past a pure chemical propulsion system, in future iterations we clearly need to do a few things:

- Increase our starship speed substantially in order to cut our transit times.
- To get to these higher speeds, we will need to use engines that have a lot higher Specific Impulses (and energy) than the chemical rockets we have been considering
- We also need to improve our power supply both to increase our power and extend its life. Consider the use of nuclear isotopes that have a much longer half-life or develop an alternative, more efficient nuclear power supply than RTGs.
- If manned, continue to improve our recycling technology.

Launch Mass Mo (t)	Empty Mass (t)	Mass Fraction	Specific Impulse	Exhaust Velocity (kps)	Final Startship Velocity (kps)	Type of Engine	Power	Mission Duration	Years to go 10LY	Comments

Starship- 2 Stage	5,200	200	26.0	380	3.7	11.6	Methalox	Fuel Cells/Solar	126 weeks	258,621	
Starship- 1 Stage	1,400	200	7.0	380	3.7	7.3	Methalox	Fuel Cells/Solar	126 weeks	410,959	
StarshipPlus- 1 Stage	4,000	200	20.0	380	3.7	11.2	Methalox	Fuel Cells/Solar	126 weeks	267,857	
Saturn VI	3,000	150	20.0	452	4.4	13.3	LH/LOX	Fuel Cells/RTG; 5kw	19 Years	225,564	
Saturn VI with Jupiter Slingshot	3,000	150	20.0	452	4.4	25.0	LH/LOX	Fuel Cells/RTG; 5kw	19 Years	120,000	Add dV 5kps from a small Jupiter Slingshot and leveraging Earths orbital velocity

Chapter 7- Saturn VII- 2050's

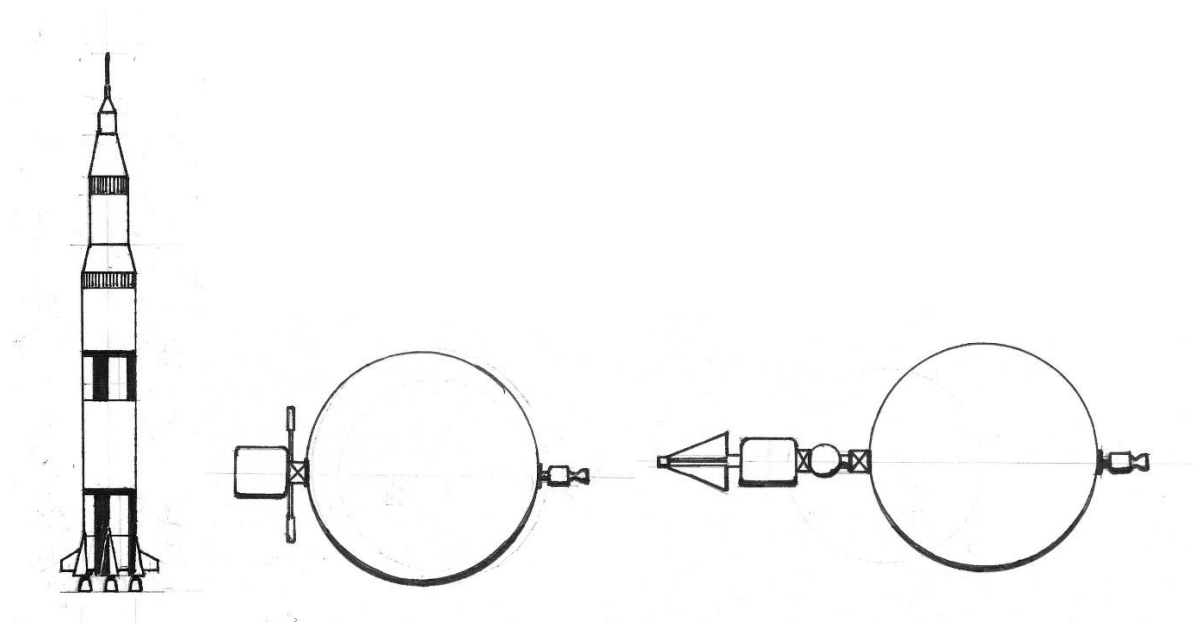


FIGURE 7-1 SATURN V, SATURN VIIA AND SATURN VIIC (TO SCALE)

If we hadn't already realized how difficult it will be to travel to a star in a reasonable time, the Saturn VI should have demonstrated that it is indeed a formidable engineering and industrial challenge. Our starship needs to get much faster as well as have a more energetic and durable power supply. If crewed, we also will need a life support system that can last for possibly hundreds or thousands of years. In addition, in keeping with my requirement of being able to be built in the 21st century we have to use known technologies, and all done within a relatively short timeframe.

With the Saturn VII we will introduce a lot of new technologies. We will still use known capabilities- all the selected engineering options would have either been flown on missions, or extensively tested on earth- but more development will be needed to make them suitable for our mission. We will consider using Nuclear Thermal rockets and Ion Engines, Stirling Radioisotope power plants and different radioactive fuels. We will also further use orbital dynamics to look at speed boosting options including an application of the Oberth powered maneuver.

Technology- Nuclear Thermal

Rather than our chemical rockets let us now consider another engine type that gives much higher performance. During a two-decade period, beginning in the 1950's and extending into the 1960s the US Government through the Atomic Energy Commission and NASA pursued development of a Nuclear Rocket called NERVA. In the mid 1980's additional work was conducted due to advances in high

temperature metals, computer modeling and nuclear engineering which further improved on the NERVA engine and was called project Timberwind.

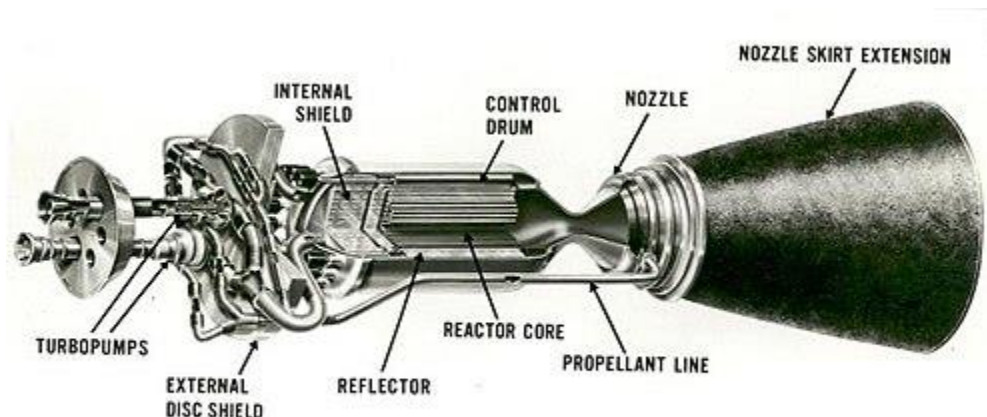


FIGURE 7-2 THE NERVA ROCKET

The advantage of the Nuclear Rocket was that it had a large Specific Impulse compared to traditional chemical rockets- about twice as high. Note that Nuclear Thermal does not get its higher performance from higher temperatures than a chemical rocket... indeed they run cooler than chemical rockets so that the nuclear fuel does not melt. Their high performance stems from the fact that in most cases they use hydrogen for a fuel (actually H_2) which has a much lower atomic mass than the water released in a LOX/LH engine- with an atomic weight of about 18.

From NERVA to Project Timberwind, it was believed that specific impulse could be raised from about 850 to 1000 seconds. Furthermore, the nuclear thermal engines being developed were quite small and compact- in one case the engine being only 1500 kg. The propellant being accelerated would be our old friend, liquid hydrogen. For our Saturn VIIA design we will go with the conservative number of 900s for a newly built engine. For our purposes, I have taken the largest of the Nuclear engines developed and tested (in 1967-1968), the Phoebus (see Fig 7-4), and tweaked some of its capabilities to come up with a slightly more capable engine with the following specifications:

$I_{sp} = 900$

Engine mass=3000kg

Thrust= 1150 kN

Flow rate=130 kg/s

Using our Rocket equation, and a MR of 20 we see that this engine would give us a Δv of about 27kps. With this flow rate, and our starting mass of hydrogen of 2850 MT the engine would burn for 22000 sec or almost 6 hours. While this duration is beyond what any nuclear test engine has operated at this does not necessarily need to be a continuous burn- depending on the design capabilities and mission profile, this may be broken up into many smaller burns. During the most intensive testing of nuclear engines in the 1960's, typical nuclear engine test runs at full power lasted for over 30 minutes.

While there would be some costs associated with making Nuclear Thermal engines “flight ready”, forty years of development and many tested prototypes make this an area of relatively low risk. If the nuclear thermal engine could substantially reduce the trip times this would be a viable option for an Interstellar “Starship”. Some issues with a Nuclear Thermal Engine include the fact that NERVA used weapons grade nuclear fuel enriched to about 85% ^{235}U (Kelvey, Nuclear Rocket Redux, 2023). Handling this enriched fuel is severely restricted by governments due to their possible use in nuclear weapons which makes further developing and prototyping very difficult. Recently lower enriched fuels are being looked at that are not as regulated.

The Powered Maneuver

The nuclear engine, with about twice the Specific Impulse of chemical rockets and therefore has twice the final velocity. This is partly offset by the tremendous size and hence mass of the LH Tank. Does the advantage of faster speed offset the greater tank mass?

It does if we leverage a powered maneuver into the equation. Nuclear engines with their greater performance allow us to take advantage of a hereto unused technique that we discussed in Chapter 2 which can add extra velocity to our rocket. With the Saturn VIIA we can take advantage of the Powered Maneuver or Oberth effect and leverage the high thrust and specific impulse of the nuclear engine to boost our speed around Jupiter.

Since the Nuclear Thermal Saturn VIIA has twice the performance of the Saturn VI, assume that we use less than half of our fuel for an initial burn that gives us about a 10kps Δv and puts it into an elliptic orbit that cuts across Jupiter’s orbit- similar to the way we used our Saturn VB and VIA on its slingshot maneuver. Now, rather than just whipping by Jupiter and just using a gravitational slingshot to change our direction, we apply a powered maneuver at Jupiter. As we plunge toward Jupiter, at our closest approach, we fire our nuclear engine again and use our remaining fuel.

In Chapter 2 we gave some theoretical performance numbers. Looking at the Figure 2-11 we can see that if we dived close to Jupiter (about 4200 km from the planets gaseous surface- or 74,600 km from its center) and applied a 10kps Δv we would gain about 35.4kps in speed- it’s as if we effectively tripled our specific impulse!

Note that one challenge with this scenario is that we want to apply as much of our delta V speed at our closest approach to Jupiter. At the speed by which we approach periapsis (nearly 70 kps) we only have a short time to apply our thrust- perhaps 15 minutes (900 sec)⁴. The Nuclear engine we proposed using might fire for several hours- far too long to maximize the potential gains. Using 900 sec as our target burn, we would only be able burn about 117,000 kg of fuel if we had a single engine. In this case if our

⁴ Note that I have arbitrarily picked 15 minutes (900 seconds). However, the spacecraft is traveling at about 70 kph at closest approach and even faster as it exits so the time to expel this exhaust is very short... the closer to instantaneous the more efficient the momentum increase will be. To actually calculate what the exact speed would be is a highly iterative process. For simplicity I have selected 15 minutes of closest approach as a reasonable approximation.

remaining Mass Ratio is about 1.78 and our Δv would be only 5kps- far less than the 10kps we were looking for. There are two simple solutions to this: either build a larger rocket engine or use two rocket engines firing simultaneously.

There are many aspects and an infinite variation in direction and speed that will determine our exact performance increase. Applying a power maneuver and factoring a small slingshot boost, it may be reasonable to reach up to 45 kps for our starship. This will be more than enough to break the gravitational bonds of the sun and send us to the stars. At 45 kps, it would still take 67,000 years to travel 10 light years.

Saturn VIIA

With the Saturn VIIA we have a starship similar to the Saturn VIA except we have a Nuclear Thermal Engine. Unfortunately, even though the specific impulse is twice that of our Saturn VI, it only reduces our voyage time by half- on the order of 120,000 years if we didn't perform a powered maneuver.

Besides the increased velocity the nuclear engine provides, it has some other advantages including a relatively small engine size, relatively high thrust to

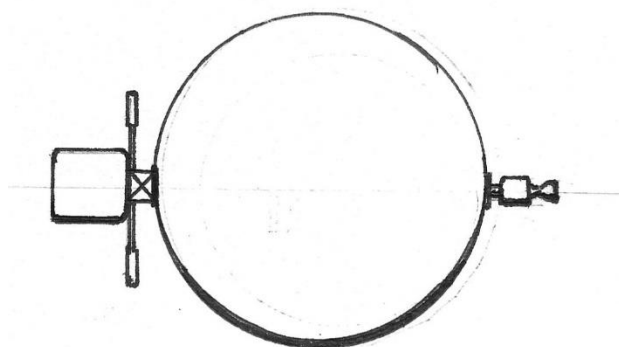


FIGURE 7-3 SATURN VIIA



FIGURE 7-4 MODEL OF PHOEBUS ENGINE AT THE ATOMIC TESTING MUSEUM

weight ratio (35:1 for the Space Nuclear Thermal program (Haslett, 1995)) and the need for only a fuel tank (no oxidizer). Nuclear engines are almost exclusively designed to use hydrogen as fuel since the low mass of hydrogen allows for a relatively high exhaust speed and hence specific impulse. However, just like the issue we had with the Saturn V and Saturn VI, liquid hydrogen fuel has a very low density and needs to be stored at temperatures close to absolute zero which will require a large, insulated storage tank.

A LH tank, of 2850 MT would need a volume of 41,000 m³. Using our original 8.4m diameter, we would need a cylindrical tank nearly 740m long. Besides not being optimized for weight, this cylinder would have tremendous surface area that would have to be insulated or blocked off from any solar radiation, otherwise our hydrogen would quickly vaporize and boil off. Like our Saturn VI, the most efficient shape would be a sphere, but now, since we don't have an oxidizer, we would

only need a single, very large hydrogen tank. As with the Saturn VI, fabricating a spherical tank in space would be difficult and may not be worth it. The simplest option is to bring up cylindrical sections and weld them together. By the time a Saturn VII were being built we should have larger diameter launchers, perhaps a 12m version. Alternatively, as proposed in Chapter V, we would send up rolls of aluminum that would be rolled into a cylindrical hoops of greater diameter and welded in space. With a 12m diameter payload our LH tank length would be a much more reasonable 340 m or so in length. This is still extremely large but volumetrically it would be easier to insulate and structurally lighter than a 8.4m diameter cylinder. The crude surface area of the 12m diameter cylinder would only be about 13040 m² vs about 19640 m² for the 8.4m diameter one. A spherical tank, would only be about 42.8m in diameter with a surface area of only 5755 m². Using our rule of thumb of 17.5kg per meter our cylindrical tank of 8m diameter will be a massive 343mt, a 12m tank would be 228mt and our spherical tank only 100.7mt. Only a spherical tank can fit within our mass budget. As mentioned before, as a spherical tank gets larger, the internal pressure increases the tension on the tank skin which requires a stronger, thicker walled tank. But as we will see later in Chapter 12, 17.5kg per m² is quite robust and will have a large margin of safety so we can stick with this number for now for a rough calculation.

Regardless we have to go with a spherical tank to keep within our mass budget and leave enough room for either a crewed mission or automated mission. Even then, the sheer size and mass of our tank will severely restrict our available mass. With our tank massing 101mt we will have to squeeze everything else into the remaining 49mt.

Item	Mass (MT)	Comments
Fuel (at mission start)	2,850	LH/LOX
Empty tank(s)	101	Spherical Tank 43m in diameter
Power Supply (5kw)	1	17 RTGs; 5000W
Engines	5	1 Nuclear Engine
Structure	20	
Payload/Supplies	23	10.7 years- a crew of three, using 2150kg of water, food and consumables per year.
Total	3000	

TABLE 7-1

Interestingly, a first cut at using nuclear engines provides less usable payload and therefore crew duration, than our non-nuclear ship. This is driven by a tremendously large (and massive) LH fuel tank.

An additional challenge with Nuclear Thermal rockets are neutrons emitted from the reactor during full power operation and heating and perhaps boiling the hydrogen at the bottom of the tank (Haslett, 1995, pp. 4-18). This can be mitigated either by radiation shielding, placing the engine(s) further away from the tank, or both.

Finally, to extend the life of the engine reactor during shut down, some hydrogen is circulated to manage the reactor decay heat (Haslett, 1995, pp. 4-19). This causes some hydrogen to be lost and this would need to be taken into account when determining the efficiency of the engine.

The nuclear engine with its associated large tank will provide far smaller mass for our payload and supplies. However it does get us is a much faster spacecraft with a reduced voyage time of 120,000 years, and if using a powered maneuver, a voyage time closer to 60,000 years.

Technology- Electrically Powered Spacecraft Propulsion

To substantially reduce our voyage times requires a tremendous increase in Specific Impulse since with a mass ratio of 20:1 our final speed will only be about 3x that of our exhaust velocity. If we increase our Specific Impulse by 10X then using the same mass ratio, our journey times will be reduced to 1/10th. Are there any rocket engines that have Specific Impulses 10x greater than a chemical rocket? There actually are - they are called electric thrusters or electric propulsion. There are two versions of electric propulsion- plasma and the Electrostatic or Ion engine of which Ion Engines are the most common. They have demonstrated Specific impulse capabilities on the order of 10X better than the chemical engines used on our Saturn VI. Small Ion engines have been in widespread use for over 50 years.

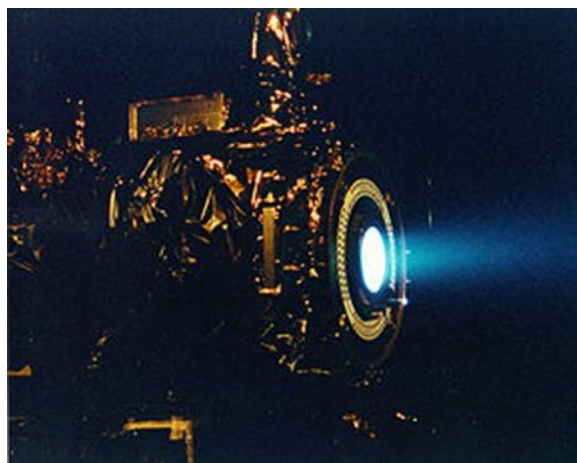


FIGURE 7-5

Each of the many types of electrically powered thrusters come with strengths and weaknesses. Some of the most researched and developed are the Hall effect, HiPEP, MPDT, LiLFA, FEPP, VASIMR, Cat, DS4G, KLIMT, and ID-500.

How do Electrical engines work? They work by ionizing atoms (through a variety of means which varies based on the type of engine) and then accelerating these ions in an electric or magnetic field (which also varies for different engines).

The theoretical specific impulse for an electrical propulsion or ion engine is:

EQUATION 7-1 $I_{sp} = \frac{v}{g} = \sqrt{\frac{2qV}{m}}$

Where:

g= gravitational acceleration

q=charge of individual ion

m= mass of individual ion

V = voltage difference through which the ions are accelerated

This equation shows that to maximize Specific Impulse we need a very high voltage and a very low ion mass.

Ion engines can use any atom as fuel. A glance at Figure 7-4 would seem to imply that Lithium (Li), Sodium (Na), Potassium (K) and similar atoms would be the preferred fuel since they have the lowest ionization energies. The noble gases would seem to be the least desirable fuel since, as seen in Figure 7-4, their ionization energies are very high. However other factors turn out to be more important- including the fact that the material should be liquid or gas so it can be stored and then pumped to the motor. Just as important is the fact that noble gases do not react with other elements which can cause erosion or wear on our electric thruster grids. The most common fuels are therefore Argon or Xenon.

When selecting fuel other factors also come into play- lighter atoms will give the highest Specific Impulse since, in a given magnetic field they can accelerate the fastest, but heaviest atoms will give the greatest thrust. Finally, the ease of storing the fuel, as well as the cost of the fuel all play into the decision on which electrical thruster and which “fuel” would be selected.

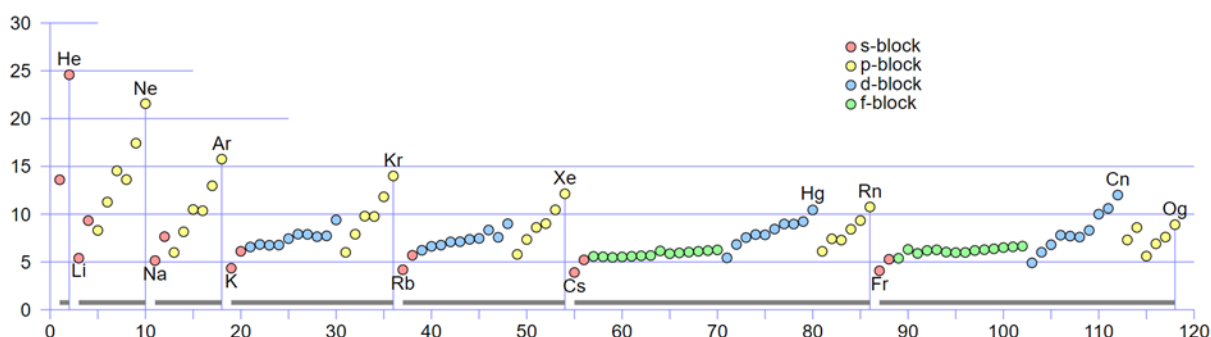


FIGURE 7-6 IONIZATION ENERGIES FOR VARIOUS ELEMENTS

In short, fuel is selected based on storability, with liquid being the best, ease of ionization, atomic weight (which help determine specific impulse), and reactivity- with the least reactive materials easiest to store and least damaging to engine components.

Many designs and types of electric thrusters have been developed or researched over the last 50+ years- the most important ones are:

Hall Effect thrusters.

These ion engines have been in use since the early 1970's and are routinely used for station keeping- including the SpaceX Starlink. There are many versions that have been put into orbit and have demonstrated extremely high reliability, but all have been very small in size, thrust and power requirements. Typically, they use Xenon, but like most ion engines, can use other propellants like

Krypton or Argon. Larger, higher power versions have been explored. Starting in 2012 Nasa began to seriously look at increasing the size and thrust of Hall thrusters with the Advanced Electrical Propulsion System (AEPS). The AEPS system that Nasa considered was a to have three 14kW units operating together with at a total power requirement of 40kW, a specific impulse of 2600 sec with each of three thrusters generating 589mN for a total thrust of 1770 mN and a mass flow rated of 22.9mg/s per engine or total of 68.7mg/s (Herman, et al., 2018).

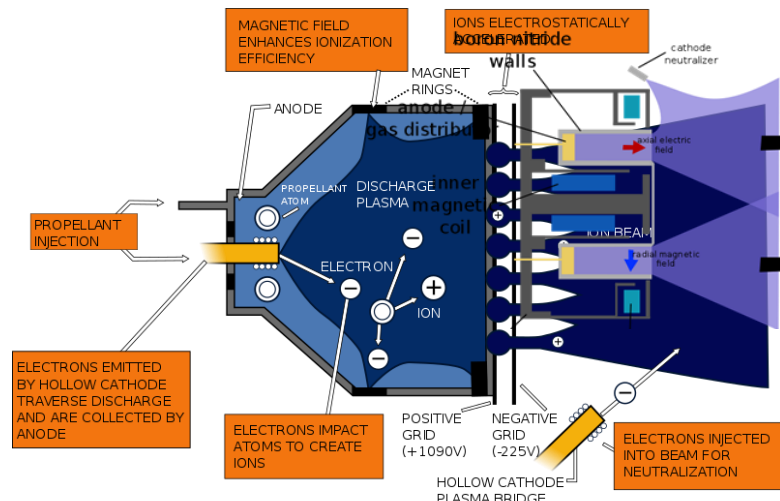


FIGURE 7-7 HALL THRUSTER (COURTESY OF NASA)

NSTAR- (Nasa Solar Technology Application Readiness)

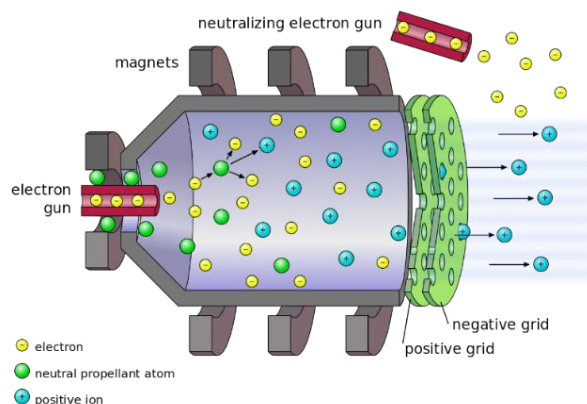


FIGURE 7-8 NSTAR (COURTESY OF NASA)

This is an electrostatic ion thruster. These have been flown on several missions, including three on the Dawn spacecraft that visited the Asteroids Vesta and Ceres. As we can tell from the acronym, these missions had ion engines powered by solar panels. They generated thrust by accelerating Xenon ions through two grids with a 1300 V difference. While these engines only generated 90 mN, they proved very reliable. Both in the lab and on spacecraft, individual engines have run for the equivalent of several years non-stop.

NEXT- (NASA Evolutionary Xenon Thruster)

This is an updated version of an NSTAR Ion engine. The NEXT thruster generates almost 3 times more force or about 236 mN and a slightly higher Specific Impulse of about 4190 seconds. As of 2020 they have not been used on any missions, but they have been built and extensively tested on the ground and are ready for future use.



FIGURE 7-9 NEXT (COURTESY OF NASA)

HiPEP (High Power Electrical Propulsion)

HiPEP both provide a higher thrust at a higher specific impulse than earlier Electric thrusters. It generates xenon ions via a combination of microwaves and magnetic fields. A pre prototype version had a thrust of 670mN using about 40kw of power and had a mass flow of 7mg/s of fuel.

Magnetoplasmadynamic (MPD) thruster (MPDT)-

This electrical plasma thruster depends on the Lorentz force to generate thrust. The advantage of this type of thruster is that they can have a much higher density of plasma and handle much more power. Because they can handle a higher density plasma, they also generate a lot more thrust than a typical ion engine.

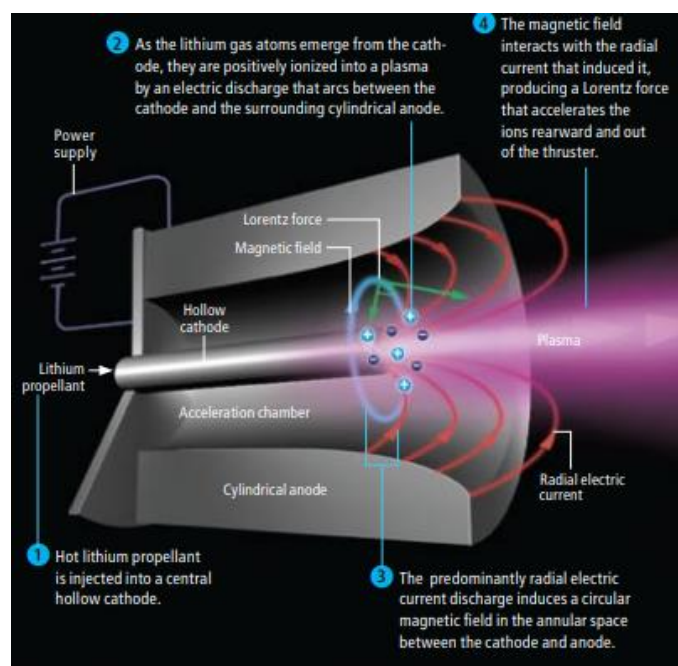


FIGURE 7-11 MPD THRUSTER

requiring 1MWe (Nasa Glenn Research Center, 2004).⁵

There remains a lot of development work to get the MPDT to the point where it is a good alternative. Unfortunately, little research appears to have been done since around 2010, possibly because the power requirements are so high that it was determined not to be a reasonable thruster for the near term.

FIGURE 7-10 HiPEP

Furthermore, they can use a wide variety of fuel, including argon, hydrogen, helium, and alkali metals such as lithium. The disadvantage is the obverse- at lower power they are not an improvement over already demonstrated Hall Effect, NEXT and NSTAR. Additional research needs to be done to demonstrate the multi-year capabilities of the proven thruster. The main reason they have not been developed further is that to have them function at their most efficient they need a large amount of power- a **Very Large** amount of power. As we have seen with our initial Saturn VI and Saturn VII, power is a major constraint. In our Saturn VI we specified a power source of only 5kW. This would be barely enough for our crew to operate the instrumentation and communication antenna and nowhere near enough to power these electric thrust engines. Some research has looked at specific impulse of 10,000 with 100nt of thruster

⁵ This referenced publication must be in error as the power required (assuming 100% efficiency) would be 10MWe using the equation for kinetic energy $KE = \frac{1}{2} \dot{m} v^2 = \frac{1}{2} \cdot 0.001(100,000^2) = 5 \text{ MW}$. I have further adjusted this number in Table 7.2 with the additional modification of assuming 80% efficiency (rather high for an electric thruster).

Variable Specific Impulse Magnetoplasma Rocket – (VASIMR)

Another plasma engine that has been in development for over 40 years between Nasa, the DOE and the private sector (Ad Astra Rocket, n.d.). The primary advantage of VASIMR as it was with the MPD thruster is the ability to handle much more power and hence thrust than the ion engines and Hall thrusters (Ad Astra Rocket, n.d.).

While progress has been made over the years, challenges remain. In tests run up until 2021, the longest duration of continuous thrust was 88.1 hours at 80kw (Giambusso, Diaz, Corrigan, Dean, & Warrayat, 2021). The primary design challenge as power has been increased is overheating and failure of the ceramic window which must confine the neutral gas. Another significant issue with high power thrusters like VASIMR is thermal control- described in one paper as “the most significant engineering challenge.” (Andres & Nikolay, The VASIMR Engine: Benefits, Drawbacks, and Technological Challenges, 2011)

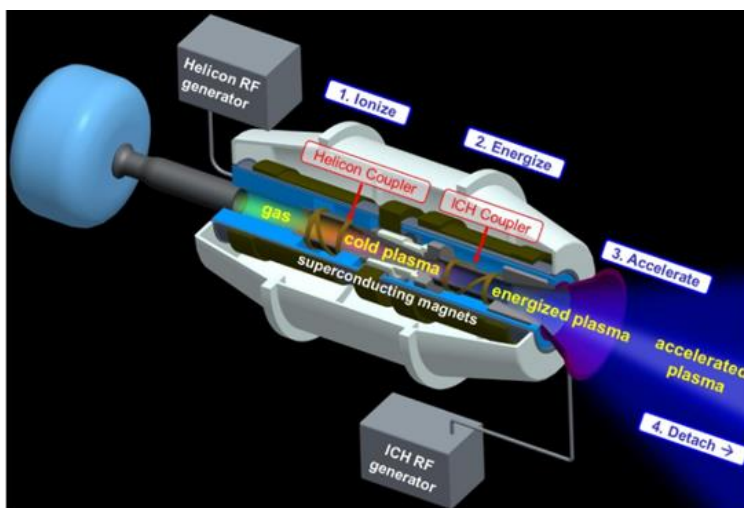


FIGURE 7-12 VASIMR

Summary of Electric Thruster Capabilities

Because of the large number of Electric Thrusters available or in development, to help keep track of them I put them in table 7-2. As identified in note 4, the published numbers for power usage is frequently less than needed based on the calculated Kinetic Energy. This is probably because the published Specific Impulse numbers are the highest the device was tested at, but the power required is more average and implies that the unit is not always operated at full power with the highest Specific Impulse. Therefore, in the Typical Power Required column I include both the top published power requirement, and below that the calculated full power requirement (in bold) with the unit operating at 80% efficiency. This is probably optimistic as most of the higher power electric thrusters operate at 40-60% efficiency (Choueiri, 2009, pp. 62-64).

	Specific impulse	Thrust	Typical Power required	Calculated Mass flow for stated power and specific impulse (x 10 ⁻⁶ kg/sec)	Comments

NSTAR	3100	90 mN	2.3 kWe 3.422kWe	2.96	Xenon; In Use for interplanetary spacecraft (Deep Space 1, Dawn)
NEXT	4200	236 mN	6.9 kWe 12.2kWe	5.73	Xenon; In Use for interplanetary spacecraft
Hall	1000-5000	40-600mN 1770mN	1.35-10 kW 40kWe		Xenon; In Use- station keeping for satellites
Hall AEPS	2600		56kWe	68.7	Xenon
HiPEP	9600	670 mN	40 kWe	7.11	Xenon. Demonstrated at 40kW. Project was cancelled in 2003
MPDT (Choueiri, 2009)	1500-6000	2.5-25N	100-500 kw	?	Hydrogen, Lithium, Ar, Xe
(Glenn Research Center)	10000	100N	6.25 MWe	1000	.001kg/sec
VASIMR	5000	6 N (Ad Astra Rocket, n.d.)	200 kWe 383.4kWe	102	Argon. Can use other elements. Ground tested. Not demonstrated in Space yet

TABLE 7-2 SUMMARY OF ELECTRIC THRUSTER CAPABILITIES

One thing that becomes obvious is that the mass per second being ejected is very small for all these thrusters. We can calculate our mass flow from formula 3-4:

$$F_{Thrust} = \dot{m}v_e$$

Where $\dot{m}$ = mass flow

Rearranging to calculate for $\dot{m}$:

$$\text{EQUATION 7-2 } \dot{m} = \frac{F_{Thrust}}{v_e}$$

To see how this works, lets use the NSTAR thruster to develop a number. Taking the published results of a Specific Impulse of 3100 we have:

$$v = I_{sp}g = 3100s \left(9.81 \frac{m}{s^2} \right) = 30,411 m/s$$

$$\dot{m} = \frac{.09N}{v_e} = \frac{.09N}{30411 m/s} = 2.96 \times 10^{-6} kg/s$$

From the above it is clear that while Electrical thrusters have much higher specific impulses than chemical or nuclear thermal rockets, they have very low thrust and mass flow.

One advantage when considering Electric Thrusters is that several of the designs are a proven, demonstrated, and reliable technology. They have been used on real missions and typically have specific

impulse's 10x that of a chemical, and five times that of a nuclear thermal rocket. Because of their large power requirements combined with low thrust, these engines are frequently used for station keeping of earth orbiting satellites where their low thrust is ideally suited for fine orbital adjustments. Electrical thrusters simplify many aspects of our chemical rocket design. For one, they need no separate fuel and oxygen tanks. Depending on the fuel, long term storage is much easier as they frequently (but not always) do not have the cryogenic requirements of liquid hydrogen or oxygen.

Selecting an electrical thruster requires looking at multiple factors such as:

- Power available
- Fuel (cost of fuel, ease of storage etc.)
- Technological readiness.

The key item that jumps out at us is that as you ramp up their thrust and Specific Impulse, is that the amount of power required goes up substantially. We will look in more detail at the power options later in this chapter. Considering what we saw with the Saturn VI where we struggled to get 5 or 8kW of power, getting the tremendous amounts of power required for the more powerful thrusters will be a challenge.

In Table 7-3 let's look at the typical fuels used for Chemical rockets and Electric thrusters.

The most commonly used elements for Ion engines are the Noble Gases, Argon and Xenon. Both are primarily obtained from the fractional distillation of the atmosphere. Xenon is a relatively rare portion of

	Boiling point	Density (at BP)	Freezing Point	Cost per kg	Comments
Earth Atmosphere	79 K (-194C)	870 kg/m ³	58 K (-215C)		
O2	90 K (-183C)	1141 kg/m ³	54 K (-219C)		
H2	20 K (-253C)	70 kg/m ³	14 K (-256C)		
Argon	87 K (-186C)	1395 kg/m ³	83 K (-189)	\$2.56	9340ppm of atmosphere
Xenon	165 K (-108C)	2942 kg/m ³	161 K (-112C)	\$1200	87 ppm of atmosphere
Krypton	120 K (-153C)	2413 kg/m ³	116 K (-157C)	\$330	1 ppm of atmosphere

TABLE 7-3 PROPERTIES OF ELECTRIC THRUSTER FUELS

our atmosphere amounting to only 87 parts per billion (ppb). Krypton is even rarer- but currently is cheaper. Argon, on the other hand, amounts to almost 1% of the earth's atmosphere- so is far and away the cheapest of the three.

Electric Thrusters have historically been very small- the Dawn robot probe that orbited the minor planets

Ceres and Vesta had a fairly large 425 kg Xenon supply (Garner, Rayman, Brophy, & Mikes, 2013). Compared to prior spacecraft, our starship would require a LOT of Xenon- 2,850,000 kg.

Historically, Xenon is the most used element for Ion engines. It has a higher atomic mass so it will provide more thrust than Argon. In addition, when stored as a liquid it is dense- over twice as dense as Argon. If stored as a liquid at high pressure it is nearly 3 times denser than water. On the Dawn spacecraft it was kept at 20C as a supercritical fluid. (Polk, Kakuda, Anderson, & Brophy, 2000). If we used Xenon for our ship, our 2850mt supply could fit into a volume 1000 m³ and could be held in a sphere only 12.5m in diameter.

Except for its lower price, Argon's primary advantage is that due to its lighter atomic mass it will have a higher engine specific impulse for the same voltage though, because of its lower mass, it will also have a lower thrust. Finally, its lower density will require a spherical tank about 17m in diameter- still very reasonable compared to our LH tank for our Nuclear Thermal Saturn VIIA.

At the cost of Xenon of about \$1000 per Kg, 2,850MT would cost about \$3.4 billion. It is likely that some dedicated atmospheric extraction and purification equipment would be built and while it is likely that building and operating this equipment will cost millions of dollars, it would be able to generate Xenon for less than \$1000 per Kg. Nonetheless Xenon would be a substantial part of our "fuel" costs.

Argon, being relatively plentiful, would likely be less than 1/1000th as much- or about \$3.4 million.

Using Ion engines to achieve high speeds for deep space missions is not a new idea. These have been used on several deep space missions, including one to several comets, as well as the Dawn probe mentioned that orbited the asteroids Ceres and Vesta. They have been long considered for more distant missions. In the late 1970's one of the earliest studies for a deep space mission powered by Ion propulsion was outlined called TAU- the Thousand Astronomical Unit- mission. This spacecraft was designed to go 1000 au in 50 years using ion engines powered by a large MW reactor (Etchegaray, 1987). To achieve this distance in 50 years it was designed to accelerate for 10 years to reach a solar system escape velocity of 106kps. Its primary purpose was to establish a long baseline to measure accurate parallax measurements to distant stars (see Chapter 2 for the discussion of parallax) as well as to measure the deep space environment (interstellar gas, radiation) between what we now call the Kuiper Belt and Oort Cloud. The TAU spacecraft as designed would have been able to travel 10 light years in about 30,000 years.

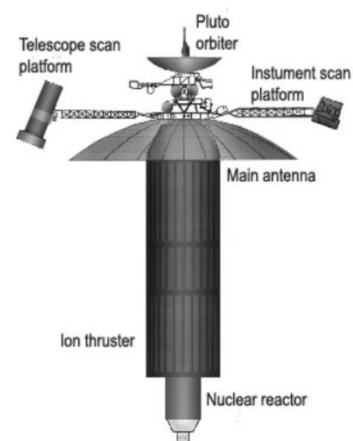


FIGURE 7-13 THOUSAND ASTRONOMICAL UNIT (TAU) SPACECRAFT

Technology- Power Options

Power is needed for both the instruments and, if manned, for life support. If using an electric thruster, most power is needed during the acceleration phase. Electric thrusters require a lot of power- indeed far more than either our instruments or for life support.

Let's say we need 30kw of power. With our Saturn VI we considered the Advanced RTG's to generate about 5000 watts of power. The low power supplied was primarily because of the low efficiency of RTGs.

Using the same technology as with the Saturn VI is just not viable- the amount of plutonium needed for a 30 kW of power is very large- we would need over 100 RTGs (with about 800kg of Plutonium) to generate this much power! One of the fundamental problems of plutonium is that it is manmade and quite difficult (i.e., expensive) to make⁶ and while potentially doable with sufficient resources, creating 800kg of plutonium will be a challenge. Finally, lest we forget, Plutonium has a half-life of 87.7 years so even a relatively short mission of a couple of hundred years will require starting off with a far larger amount of power. Assume we have a mission of about 260 years (3 generations of plutonium half-life). If you wanted 30kw of power at the end of the mission you would be starting off with almost 120 kw of power or 4x more. You would need over 3200kg of plutonium.

As in many things in the real world, there are some options. We have two, somewhat independent problems. One is generating enough power for our spacecraft and the other is generating this power for thousands of years.

Ways of Generating Power

The need for lightweight but abundant power is a major issue when it comes to interstellar travel. If we had unlimited power, we could install 100 HiPEP engines or even 10,000! and quickly accelerate. If we had 10,000 engines, we would have enough thrust to still get a reasonable acceleration of even a large starship. A very light weight power supply may allow us to increase our mass ratio. Suppose we increased our mass ratio to 200 to one? This would increase our speed to over 5x our exhaust velocity- with the HiPEP we are now approaching 500kps (but again, the actual performance would be far lower... the gravity losses would be substantial). Unfortunately generating large amounts of power has never been done in space and most schemes for doing so are very heavy.

A NASA chart (Figure 7-14) neatly summarizes all the options available for a spacecraft (Lyons V. , et al., 2010).

Solar is viable for generating a fair amount of power with a relatively low mass and could last for many decades- but of course we would have to operate near our sun- clearly not an option for our starship.

Chemical energy takes many forms but includes the fuel cells described for the Saturn V as well as batteries. Fuel cells can provide large amounts of power for short amount of time, or less power for longer... technically they can last forever as long as you keep supplying the hydrogen and oxygen.

At the bottom right of Figure 7-14, Radioisotope/passive were what we used for the Saturn VI- our RTGs. The problem with Radioisotope/passive is that they are tremendously inefficient for a given watt of electrical power. The first thing we must do, no matter what else, is improve our efficiency.

Just above the Radioisotope/ passive portion of the graph is the Radioisotope/dynamic. This refers to the Advanced Stirling Radioisotope Engine (ASGR). This generator is a variation of a reciprocating engine

⁶ This is not actually true. During the cold war and through the early 1980's plutonium was made in large quantities for weapons. However, for budget, and even more importantly political reasons, this capability was allowed to lapse and the United States has been obtaining most of the plutonium it now uses from Russia.

and is about 2-4 times more efficient than our baseline RTG per kg of fuel. Let's assume they have an overall efficiency of 25%. This would be a large improvement and reduce the amount of plutonium per watt generated by nearly 75%. Because of its much greater efficiency the ASGR is one option we would look at. The problem with the ASGR, vs the RTG is that the ASGR is mechanical and therefore has moving parts that can fail. Currently design efforts are working to extend the life of the ASGR so that they can operate reliably for a few years of operation. However, for our starship needs, considerable design work needs to be done in order for them to last decades. In addition, current design work focuses on

relatively small generators as they would be a direct replacement for RTGs. For our purposes, due to the large power demand for the NEXT Engine, we would want to design a much larger ASGR. If we were to stick with the design as currently proposed, the NEXT engine would need almost 25 ASGRs.

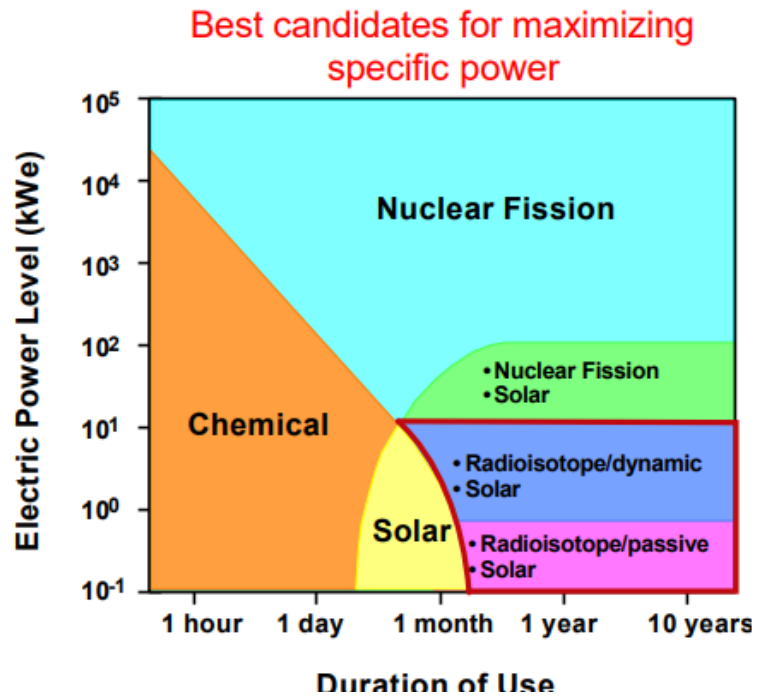


FIGURE 7-14 NASA POWER CANDIDATES FOR SPACECRAFT (LYONS V. J., ET AL., 2012)

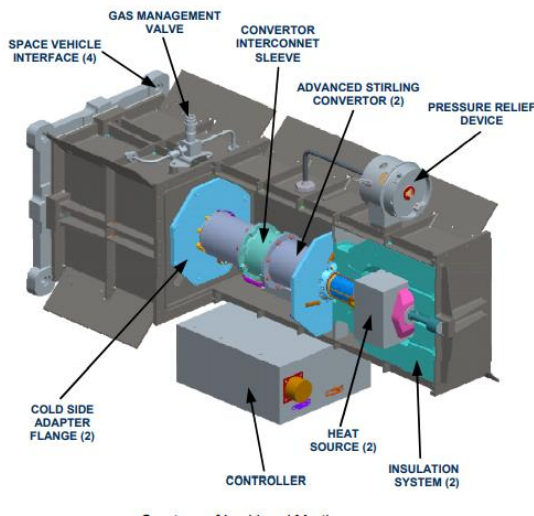


FIGURE 7-15 STERLING POWER GENERATOR (COURTESY NASA)

Generating it for Centuries

Even if the mechanical issues with creating a reliable Generator that can operate for many years were solved, the typical Stirling Generator still requires a large amount of plutonium which, with its limited half-life, will only power us for a century or two.

Because of this we will have to look at alternate fuels with longer half-lives. The short half-life of Plutonium explains why there is no naturally occurring plutonium in the earth's crust. Any plutonium created by a star super-nova would have decayed within a few thousand years- far longer than it took the earth to form.

Fortunately, Plutonium is not the only radioactive element we can use, and we can pick elements with far longer half-lives. Americium is one such element-

it has a half-life of 432 years. Using Americium and extending for six generations will give us about 2500 years of power- well short of the duration needed- but still 5x better than plutonium. But while this fuel has four times the half-life, it has only about 30% of the power density- 114.7 mW/kg vs 390mW/kg for ²³⁸Pu. To get the same power out of Americium you will need four times the fuel mass. In addition, ²⁴¹Am poses a greater health risk for a manned mission since it emits more gamma and neutron emissions. Even though ²⁴¹Am is, like plutonium, manmade, it is more plentiful, and the radiation issues are manageable.

For a nominal 100,000-year mission would “only” involve 231 generations of Americium our power is down to a much more manageable 3.45×10^{69} watts- but even this number is still more than the universe creates!

Summary of Nuclear Power Options

Below I have tabulated and summarized some current and reasonable future options for nuclear power generation. In the following chapters I will go into more details on the strengths and weaknesses of each.

Power Supply	Watts Thermal	Electrical Watts	Fuel Weight kg	Generator Mass in kg	Electric Power per Reactor Mass Watts/Kg	Comments
Radioisotope/ Passive						Currently available power source
Voyager- 3 MHW- RTGs	7,200	471	13.5	113	4.2	
Cassini- 3 GPHS- RTGs	13,200	900	23.4	171	5.3	Considered for Saturn VI
Radioisotope/Dynamic						Research and Design work done but more needed
Advanced Stirling Radioisotope Engine (ASGR) (Plutonium)	500	135	1.2	32	4.2	Considered for Saturn VII
Super ASGR (Plutonium)	5000	1350	12	320	4.2	Enlarged version of ASGR. Considered for Saturn VII
Super ASGR (Americium)	5000	1350	41	320	4.2	Enlarged version of ASGR. Considered for Saturn VII with Americium and 4x the half life

Fission						Reactors are common on earth but never built for space
KRUSTY	43.3kW	10 kW	44kg Highly Enriched	1500	6.67	Considered for Saturn VIII. 12-15years operation. Used highly enriched Uranium
Advanced Space Nuclear (ASN)	750 Kw	250 kW	1000 kg over 15 years	25,000	10	Highly Enriched. 12-15 years operation. Considered for Saturn IX and X
Nuclear Aircraft Carrier Vessels A1B Reactor	700 MW	125 MW		10,000 MT?	12.5	The design of military reactors is Secret. I have speculated the power plant weighs 10% of the carrier's weight. Operates on enriched uranium.
Typical Earth Power Reactor	3000 MW	1000 MW	25mt enriched 100mt natural			Annual Fuel Usage (3-5% enrichment) (Usually 25% of total fuel is changed out per year)
Super Space Nuclear	3 GW	1 GW	25 mt	10,000 mt	20	Saturn C and beyond

TABLE 7-4 COMPARISONS OF SPACE NUCLEAR POWER SUPPLIES

What this table tells us are:

- The watts per kg of reactor weight do not improve tremendously from design to design for a particular power plant type. Any power plant we build will be heavy. This is driven by many things including the need to have radiation shielding, large turbines and radiators to shed waste heat.
- The weight of the fuel IS affected by the technology selected due to efficiencies of generating power. Stirling and traditional fission reactors get a LOT more power out of each Kg of fuel compared to RTG, but the overall complexity of the more advanced power plants does not have a huge effect on the watts per Kg of the power plant.
- RTGs and the ASGR are powered by the heat given off in the decay of plutonium. Except for some experimental test satellites, most of the nuclear sources launched into space are of this type. Further in the future the development of nuclear fission reactors like those on earth as well as nuclear powered naval ships, will need to be used. To date, no large fission reactors have been launched into space and it is likely that their development will take many years. In future iterations we will have to consider using Fission reactors. Fission reactors typically use ²³⁵U for fuel.

Based on a reasonable development path over the next thirty years, the ASGR would likely be the most viable power supply available. Even though a long-term working model has not been built, many aspects of its design have been tested individually and the technology is well known. However, even this relatively simple step up from RTGs is not ready for “prime time”. The ASGR was designed to generate about 135 watts of electricity- this is nowhere near enough for our purpose. In addition, substantial engineering challenges remain. The one long duration test that has performed in 2014 demonstrated an excellent conversion efficiency of 28.6% but started experiencing excessive power fluctuations after only about 179 hours of operation (Lewandowski, Dobbs, & Oriti, 2016). This is only a fraction of the possibly hundreds of years of operation we would want and was described with understatement in a report as “such an early failure was both unexpected and disconcerting” (Lewandowski, Dobbs, & Oriti, 2016, p. 2).

Regardless, to be able to generate more power, we will have to migrate beyond the RTGs used in the past. The ASGR would be much more efficient than our traditional RTGs and with substantial engineering research we should be able to improve on their durability, but as seen in Table 7-2 all the electrical engines require much more power than the proposed ASGRs. To power any of the higher performance ion engines requires thousands of watts and would require dozens of ASGRs. If we pick an overall target of 10 kW at the start of the mission, we will need nearly 100 of ASGRs. While the ASGRs are designed to be modular so this could be done, it does not seem practical. Instead, I would propose extrapolating to a much larger (10x) “Super” ASGR which would generate 1350 electric watts from about 12 kg of ^{238}Pu or about 40 kg of ^{241}Am .

If we want to go to a far higher amount of power, we will have to switch to a fission reactor. For our Saturn VII we will not consider this since Fission reactors, while common on earth, have never been used in space and a lot of design work will need to be done to make them feasible. We will consider fission reactors for the more advanced Saturn VIII.

Other than nuclear sources, are there other power generation schemes that could replace or supplement the nuclear requirements? One option we may consider is- do we have any power supply available at the end of the mission that can supply enough power to activate and run our equipment but does not depend on radioactive isotopes that would have long since decayed? Would a fuel cell help us? If Oxygen and hydrogen were kept separate during the long journey but then introduced into a fuel cell when approaching the star, we could generate power this way.

Remember we considered fuel cells to generate power on our Saturn VB manned. In that case the fuel cells were used to generate a continuous 5000 watts for 20 years. In our new case, we would use only a trickle of fuel cell power or, even more efficiently, our RTGs until we arrived at our destination. Even after several centuries the RTGs would only need to have enough power to switch some valves that reactivated the fuel cell and then we could generate substantial power at the end of our mission (even if only for a short time)- perhaps to run our instrumentation during a star systems flyby.

How much hydrogen and oxygen is required? As noted before Hydrogen has a value of 33 kwh per kg. For a fuel cell that is 50% efficient you would only generate about 16 kwh per kg. Let's assume that to run our instruments and transmit our information back to earth we needed 1000 watts. To generate this you would use .06 kg of hydrogen per hour. To operate the equipment for 1000 hours (about 40 days) you would need 66.7kg hydrogen- but 8x more oxygen- or 600kg total.

Note that using a fuel cell at a very low power rate of 10 watts for 40 days you would only use 1/100 of this amount, or 6kg combined oxygen/hydrogen. In the course of a year, you would use only about 55kg. For 1000 years you would use only 55,000 kg.

This is not an improvement over a Stirling Engine Radioisotope power supply. About the only thing I can see fuel cells being used for is perhaps at the end of the trip. The Nuclear power supply would be used for running the mission and engines at the beginning of the mission, but at the end, they would just need to generate enough power to activate a valve to start of the fuel hydrogen and oxygen to flow into the cells. For a 22,000-year mission we would need 51 Americium generations. If we started with 35,000 watts at the beginning, we would be generating only 13.5watts at the end – sufficient to activate our fuel cells. The Fuel Cells can then power the science experiments for the one or two months of science needed. Keep in mind that the mechanical Stirling generator would probably not be able to operate at so low an output so some sort of traditional RTG capability may still be needed which would only generate about 3watts of power.

Saturn VIIB- Electric Thruster

For a Saturn VII, a low technologically risk approach would be to use ion or plasma engines that we have a high level of confidence in- those that have either been used on missions or have a lot of test stand operation demonstrated performance. This would limit us to a few decades of development ahead of us, the only Electrical thrusters we have a very high confidence level that will perform as theory states are the NSTAR, NEXT, Hall and HiPEP. Let us consider some of these each in turn.

The specific impulse for the NSTAR Ion Engines on Dawn was about 3100 sec. However, these engines provided a very anemic 92mN thrust at 2100 watts. For a 3million kg rocket this will provide incredibly small acceleration.

“Next” up in both performance and thrust is the next generation ion engine- NEXT. The NEXT specifications are:

$I_{sp} = 4190 \text{ sec}$

Thrust= 236 mN or about 2 ½ times more thrust at 6900 watts of power

This is still a very low thrust. If we combine 4 of these engines it would provide about 1N of force. While this is still very small compared to chemical or nuclear thermal rockets it is over 10x more thrust than NSTAR. For 1N thrust we would need about 30,000 watts of power. We can consider this as one option in our Saturn VII.

Using our proposed “super” ASGR (SASGR) we would need about 22 generators each with 12kg of plutonium for a total of 267kg. That is a lot of generators and a lot of plutonium (but still only ¼ what the RTGs would have required). The ability to manufacture plutonium would have to be expanded tremendously. So even the relatively small requirement of 30kW of power will be a huge technological and industrial challenge. For this reason, as well as the four times longer half-life, we should consider a switch over to ²⁴¹Am. With Americium we would need about 880kg of fuel.

NASA tested a prototype NEXT engine over several years in a test stand. During the multiyear tests the NEXT engine processed about 900 kg of xenon propellant and had over 50,000 operating hours- or about 5.7 years. This works out to have a mass flow rate of 5×10^{-6} kg/sec. This is closely in line with our calculated rate of 5.73×10^{-6} . This also compared favorably to the original design goal of 750 kg of throughput per engine before failure. If we had four engines, we would have processed 3600 kg during those 5.7 years (or about 632kg per year). Extrapolating for our Saturn VIIB, to use up 2,850,000kg of xenon fuel the engines would have to operate for 4513 years- a challenging prospect indeed. There is a life limit to these engines because of wear on their components, but in particular their acceleration grid. The NEXT engine test far exceeded the original 750 kg target, and it may be reasonable to extrapolate further improvement that each engine might be able to handle 1000kg or even 2000kg. However, designing an engine or engines that can operate for several millennia as well as a power supply to generate power for 4500 years is beyond our capabilities. With the NEXT engine, disregarding the gravity losses of exiting the sun (which would be substantial), we could have a total Δv on the order of 120 kps.

We can also consider the HiPEP engine which provides a considerable bump up in capabilities. This engine has some significant performance advantages- but HiPEP is less developed and requires more power for a similar amount of thrust. The advantage to HiPEP is a significant increase in Specific Impulse- about twice that of NEXT. If we used two HiPEP engines our thrust would be about 1.3N- but our power requirements would be about 80,000 watts. While this is substantial compared to historical power requirements, it is less than $1/10^{\text{th}}$ that proposed for the TAU mission. The HiPEP thrusters, again disregarding the gravity losses, could provide a Δv of nearly 290kps. Our mission time out to 10 LY's has now down to a little over 10,000 years!

If only it was that simple- our thrust and mass flow is so low (only about 1.4×10^{-5} kg sec for two engines) that we would only consume about 441kg of reaction mass per year. To go through our 2,850mt of fuel would take use 6463 years. If we used four engines this would drop in half, but our power requirements would now be 160,000 watts. In addition, as with all the electric thrust engines the low force of the electric thrusters means we would not quickly break free from the sun but instead spiral slowly out over centuries or millennia before we would break free... the gravity losses incurred would substantially lower our final velocity. To use the HiPEP as an example suppose our starship thrust is 1.3n but our spacecraft mass is 200,000kg. Let us calculate the distance the probe would need to be from the sun so that its thrust would equal the gravitational force of the sun. From Equation 2-1:

$$F = G \frac{(m_1 m_2)}{r^2} = 1.3n = \frac{(6.672 \times 10^{-11})((1.9885 \times 10^{30})(5.972 \times 10^{24}))}{r^2}$$

Solving for r we get:

$$r = \sqrt{\frac{G(m_1 m_2)}{F}} = \sqrt{\frac{(6.672 \times 10^{-11})(1.9885 \times 10^{30})(200,000)}{1.3}} = \sqrt{2.041 \times 10^{25}}$$

$$= 4.518 \times 10^{12} m = 4.518 \times 10^9 \text{ kilometers}$$

Which works out to 30au. This is an oversimplification as this would imply an object standing still in relation to the sun, vs the reality that an electric thrust rocket would already be in an orbit at a considerable velocity, but it demonstrates the extremely low thrust level of ion engines. To calculate the

exact trajectory of a spiraling object, including when it will eventually break free from the sun, is very time-consuming and not easily calculated.

Saturn VIIC- Two Stage Hybrid

Because of the low thrust and high power demands a Saturn VII size starship would not be a practical solution to reach for the stars. However, all is not lost, and one could imagine a two-stage rocket whereby the first stage is nuclear thermal rocket that does a powered flyby past Jupiter and after the flyby would discard the first stage and only then start up our Ion engines. How would this two-stage mission work?

Let us assume a nuclear engine with a specific impulse of 900 and a MR of 10. Using approximate

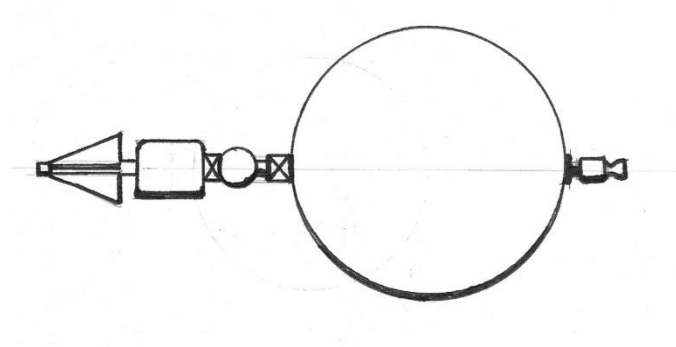


FIGURE 7-16 SATURN VIIC- TWO STAGE

numbers, a mass ratio of 10 gives you a final velocity about 2.3x that of the exhaust velocity or just under 20kps. This first stage would use about 2700 mt of hydrogen- or over 25x more than the SS carried. Using the approximate density of LH as .0699667 kg/m³ we will need about 38,600m³ of hydrogen. Our empty fuel tank, assuming we use the efficient spherical configuration, our diameter is about 41.93m and surface area 5,520m². Using our 17.5kg/m² mass, we come up with a total mass of about 96,600kg or 96.6mt. We assume

(optimistically) that the balance of the additional stage 1 mass is 3.4mt. This is unlikely as the stated mass of the Nuclear Thermal rocket was 3mt. I will assume we are able to lower our tank mass somewhat by clever and aggressive engineering and material selection. If we could lighten our tank mass to 15kg/m² our tank would now be 82.2mt and we should have enough remaining mass for a Nuclear Engine and our structure.

In this scenario we would have both the first and second stage with a 10 to 1 MR. However, this does not reflect what is really happening. Table 7-6 shows that a two-stage rocket, because of the massive deadweight of its hydrogen tank, will not have the payload performance we were hoping for.

As with the Saturn VIIB, the HiPEP would provide a higher 9600sec Specific Impulse for 1.3N thrust but with our two-stage configuration we have a lot less mass to play with. HiPEP would require 80kw and using our rule of thumb of 4.2W of power per kg of generator mass our power plant would weigh about 19,000 kg... this would leave only 1mt for all our remaining hardware- including our Xenon fuel tank- which is not feasible. With the Saturn VIIB, HiPEP could be an option but for the Saturn VIIC we would settle on using four NEXT engines, and a thrust just under 1N because of the small payload and structure mass available.

With four NEXT engines, we would “burn” through our fuel at about 2.23×10^{-5} kg per second. We have 180mt of Xenon. This will last for 8.0717billion seconds, or 256 years- far less than the 4500 years

calculated for the Saturn VIIB. With the Americium half-life of 432 years, we need to start out with about 50kw to account for the power drop off. This would be provided by 37 SASGRs and using our rough rule of thumb from Table 7-1 of 4.2 watts per kg of reactor weight, our reactor would weigh 11.9mt. This would leave 8.1mt for our instruments, Xenon storage tank and engines... which is probably doable if challenging.

Our 180mt of Xenon propellant could fit in a spherical tank only 61m³, equivalent to a spherical tank 4.9m in diameter and mass slightly less than 1.5 tons. I have rounded up to two tons to include all the other support structure in Table 7.4.

Based on a projected lifespan of 10,000 hours (demonstrated) per NEXT engine, this implies that each engine would last about 1.15 years. We will need a total of 890 NEXT engines (firing 4 at a time) over the 256-year acceleration period. The actual electrical thrusters weigh on the order of only 12kg each (for a total mass of 10.7mt) but considerable additional weight is tied up in propellant management, thermal control, and power units. I assume much of this mass can be reused and assume we can develop an engine that has a lifespan about twice that currently demonstrated. For simplicity I will assume that our total mass of engines, associated equipment and spares is about 5.4mt.

	First Stage (in metric tons)	Second Stage (in metric tons)	Payload (in metric tons)	Totals (in metric tons)
M_{structure}	100 (82 fuel tank; 3 NERVA engine; 15 structure); 42m diameter tank	20 (Payload total)	35kw power supply (11.9mt); Engines and spare engines (5.4mt) Xenon Tank (2mt) Payload (.7mt)	120
M_{Propellant}	2700	180		2880
M_{total}	2800	200		3000
M_{empty}	300 (200+100)	20		
Mass Fraction	3000/300 = 10	200/20 = 10		
Isp	900	4200		
dV	20 (rocket- 10 earth, 10 Jupiter) 40 after powered maneuver	97		137

TABLE 7-5 SATURN VIIC TWO STAGE HYBRID

If we had a magical power supply that could provide us the necessary power and allow us to stay within our mass budget, we could achieve a substantial performance increase. If we used the HiPEP electric

thrusters in our second stage, with a mass ratio of 10, our performance would likely be closer to 220 kps- a truly impressive performance. To this we add our initial stage 1 boost of 40kps for a total of 260 kps. Now our voyage would be on the order of 12,000 years. Unfortunately, this performance rests on the development of a high power but relatively light weight power supply- which will not likely be available in time for our Saturn VII. Over the next 20-30 years the most likely power source would be some version of the Stirling Reactor driven by Plutonium or Americium.

Cost

As we get further in the future and our designs get more speculative costs will become even more of a guess. Regardless, the additional engineering and development required for the Saturn VII means that costs will be greater than the Saturn VIA. With the Saturn VIIA we will need to design an updated Nuclear Thermal Engine and revive our ability to manufacture them. In addition, the massive size of the hydrogen tank will make for a much more complicated and challenging in-Space construction.

Saturn VIIA Activity	Cost (Billion \$)	Comments
Design Saturn VIIA	\$3	Rocket Component Design including spherical tank
Engine Research and Design	\$3	Develop, design and test new Nuclear Thermal Engine
Construction of Saturn VIIA Rocket	\$3	Component Construction Costs on Earth
Payload Design and Construction	\$3	Design of Water Separation system, Habitation Module, Communication
Power Design	\$2	Develop a ASGR
Payload Construction	\$1	Habitation Module Construction
Launch Costs	\$10	200 launches, 100mt per launch; \$50million per launch; 30 Launches for Saturn VIIA, 30 launches for Manufacturing Station; 140 launches for support and construction materials
Design of Space Manufacturing Station	\$4	For construction of Starship to include advanced welding capabilities to construct Spherical Tanks
Construction of Space Manufacturing Station	\$5	Mostly Component Construction on Earth
Research and Development of key space manufacturing technologies	\$2	Cutting, Welding and Forming of metal sheets
Construction Costs in Orbit	\$2	Personnel; equipment; supplies

Total	\$38	

TABLE 7-6 COST FOR SATURN VIIA

With our Saturn VIIB, costs will likely be similar. We will need to spend a bit more on designing of large Stirling Generators – the Super ASGR (\$3billion instead of \$2billion), as well as money to pick on and develop the best Electric Thruster (\$1billion), but we will save money by not needing to design a new Nuclear Thermal Engine (\$3billion). Furthermore, the Electric Thrust engines require such a small fuel tank that we will simplify our space manufacturing (though savings are likely to be minimal).

The Saturn VIIC will need to include both the development of a Nuclear Thermal engine (\$3 billion), manufacturing capabilities for large, welded tanks (\$2billion), and the development of high power Stirling Generators (\$3billion). The combining of these technologies into a two-stage starship will also add some costs. I would anticipate total costs to be in the \$42billion range.

Saturn VIIC Activity	Cost (Billion \$)	Comments
Design Saturn VIIC	\$4	Rocket Component Design including spherical tank; Two Stage configuration
Nuclear Engine Research and Design	\$3	Develop, design and test new Nuclear Thermal Engine
Electric Thruster Research and Design	\$1	Building on and refining already demonstrated technology
Stirling Reactor Research and Design	\$3	Development of Super ASGR
Construction of Saturn VIA Rocket	\$3	Component Construction Costs on Earth
Payload Design and Construction	\$3	Design of Water Separation system, Habitation Module, Communication, Power
Payload Construction	\$1	Habitation Module Construction
Launch Costs	\$10	200 launches, 100mt per launch; \$50million per launch; 30 Launches for Saturn VIIA, 30 launches for Manufacturing Station, 140 launches for support and construction materials
Design of Space Manufacturing Station	\$4	For construction of Starship to include advanced welding capabilities to construct Spherical Tanks
Construction of Space Manufacturing Station	\$5	Mostly Component Construction on Earth
Research and Development of key space manufacturing technologies	\$2	Cutting, Welding and Forming of metal sheets
Construction Costs in Orbit	\$2	Personnel; equipment; supplies

Total	\$41	

TABLE 7-7 COST FOR SATURN VIIC

Summary and Conclusions

Even though we are far short of our goal, we are making progress! In this chapter, both the Nuclear Thermal and the Electric thruster were considered. While both showed improvements, we only got substantial improvement when we combined both in a two-stage rocket where each stage had a mass ratio of 10. With the requirement of two stages, part of the first stage mass gets dropped and cannot be included in our second stage mass ratio, so the reality is that our final payload was only 1/150th of the starting mass- or 20,000kg, of which only 700kg was instrumentation.

With the Saturn VIIC we used a couple of Nuclear Thermal engines and performed a powered maneuver around Jupiter to achieve an escape velocity of about 40kps. While clearly insufficient as a standalone velocity target, we considered using this as a first stage booster for a NEXT ion engine second stage.

Our second stage also had a mass ratio of 10 and consisted of a large Stirling Engine power supply powered by Americium and generating 50kw at the start of the mission. This Starship would be propelled by 4 NEXT engines that would provide about 1 nt of force for almost 260 years.

With this configuration our two-stage rocket would be able to achieve a final velocity of about 137kps. This appears the most practical solution using these technologies for a starship. An ion powered starship without the first stage boost would get a far lower dV even though, on paper, its performance would be higher. In reality this sort of spacecraft would gradually spiral further and further out of the suns gravity well- but since this is not a single pulse of thrust, but rather spaced out over decades, most of this delta v would not translate to useable speed... gravity losses would mean our final rocket speed would be far lower than the 120kps of theory. If we launched our ion powered starship as the second stage after the initial nuclear rocket powered first stage booster, our velocity would be 160kps.

One final thought experiment- similar to what we proposed with the Saturn VI, let us carry the nuclear rocket to an extreme and put our 150,000 kg payload on an Icy Planetoid that weighs 483 million times more than our payload. If we use our standard nuclear engine Isp of 900 seconds, we will have a final velocity of 175kps. While still to slow for a reasonable trip time to the stars, this is an impressive speed. It should be noted that if we followed a similar concept of using electrolysis to separate the hydrogen and oxygen, only hydrogen has been used for a typical Nuclear Thermal rocket. But based on the atomic weights the Oxygen is 8x heavier than hydrogen in water, therefore with our current engine designs we would waste or throw away 89% of the water mass in the planetoid, leaving only 1/9th the mass to accelerate. A nuclear engine can use Oxygen as a fuel, but Oxygen is a very reactive chemical and would cause a lot of erosion to our nuclear engine, and I am not aware of any engineering tests done using oxygen as the reaction mass. Furthermore, the higher atomic mass of oxygen would lower the exhaust velocity considerably. The same problem would exist if we tried using water for our exhaust- the high weight of the water molecule would reduce the Isp. Either way, to use water or oxygen vs hydrogen would require considerable redesign of the nuclear rocket and likely not worth it.

In the next Chapter we will push the technologies discussed in this chapter to the next level to see how far this process can go...

	Launch Mass Mo (t)	Empty Mass (t)	Mass Fraction	Specific Impulse	Exhaust Velocity (kps)	Final Startship Velocity (kps)	Type of Engine	Power	Mission Duration	Years to go 10LY	Comments
Saturn VIIA	3,000	150	20.0	900	8.8	50.0	Nuclear Thermal	Sterling	11 years	60,000	Jupiter Powered Maneuver of dV 14kps
Saturn VIIB	3,000	150	20.0	4200	41.2	120.0	Electric Ion- NEXT Engine	Sterling/35k w/Americum	11 years manned; 250 years unmann ed		Theoretical velocity; because of gravity losses will be much less; Engine will need to operate for 4500 years
Saturn VIIC	3,000	20	NA	4200	41.2	137.0	Nuclear Thermal/ Electric Ion- NEXT Engine	Sterling/35k w/Americum	250 years unmann ed	21,898	Two Stage; powered maneuver around Jupiter; workable; only 20mt empty final stage; Stage 1- 40kps, Stage 2- 97kps

Chapter 8- Saturn VIII- 2060's

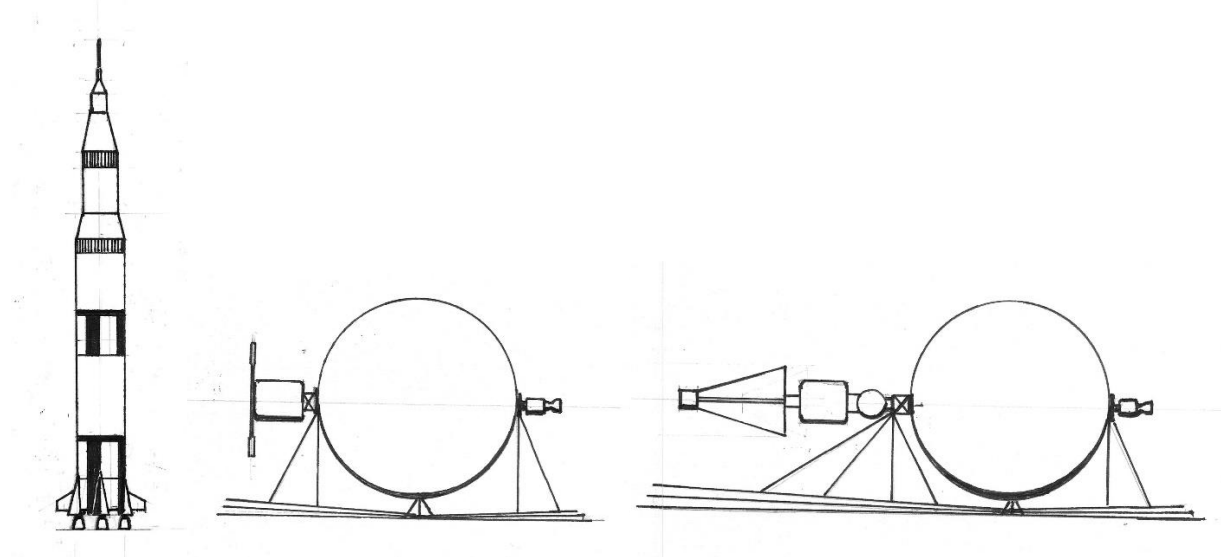


FIGURE 8-1 SATURN V, SATURN VIIIA AND SATURN VIIIC (TO SCALE)

In the prior Saturn iteration, we bumped up our speeds with various new technologies. We introduced both the Nuclear thermal engines and Electric Thrusters. We also introduced the SASGR for Power. In this version, with 10 more years of research we will attempt to use many of these same techniques but maximize them. Most importantly, with improved Nuclear Thermal engines, we will bump up the specific impulse and do a more aggressive Oberth maneuver around the sun instead of Jupiter. With the Electrical Thrusters, we need to have considerably more power available than the SASGR provides. In this iteration we will consider advanced and larger fission nuclear reactors.

Saturn VIIIA- Nuclear Thermal improved and the Power Maneuver

With the Saturn VIIIA we will assume a reasonable but slight increase in our Nuclear Engine performance. More importantly, we will consider a more complicated and aggressive powered maneuver using both Jupiter and the sun. As we saw in Chapter 2, the velocity gains achieved by using the sun for an Oberth maneuver are substantial- in theory it can be much higher than using a planet, even one as massive as Jupiter. However, the advantages of using the sun are offset by substantial problems – approaching the sun close enough to maximize the powered maneuver, but not so close as to melt your ship, and almost as bad, boiling off your hydrogen fuel before you can burn it!

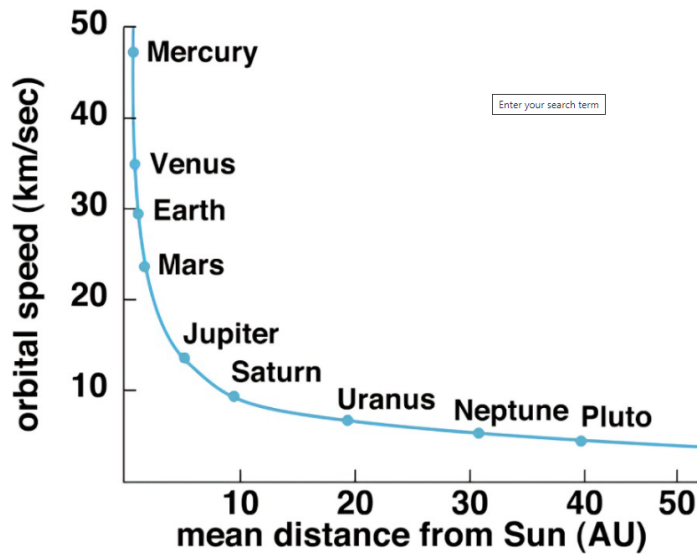


FIGURE 8-2 ORBITAL VELOCITIES AROUND THE SUN

The first challenge is that you must effectively negate the earth's 30kps rotational motion. Getting close to the sun can be a challenge. If you are in orbit around the sun to get closer to the sun, you must drop your orbital speed. If we dropped an object from a point way outside of the solar system (effectively near infinity) we would hit the sun surface at the same speed as its escape velocity- or 614kps. If we stopped all orbital motion from an object that was at the earth's orbit, we would need to remove the 30kps orbital velocity so the object would drop straight down toward the sun. We would hit the sun's surface at a speed a little less than its escape velocity since we did not approach the sun from infinity. In the real

world we don't have rockets that can negate the earth's 30kps velocity. Furthermore, we don't usually want our spacecraft to plunge into the sun. Instead, we would like our spacecraft to be in an extremely elliptical orbit with its perigee near the sun so as to perform a powered maneuver.

Eliminating most of the 30kps of the earth's velocity is difficult and frequently done via multiple slingshot maneuvers, usually using the Earth, Venus or Mercury. The best example of this being the Parker Solar Probe that, which, by using multiples reverse slingshot maneuvers with Venus, has been able to approach within 10 Solar Radii of the sun (or 6.9 million kilometers). At its closest approach, the probe is traveling up to 690,000 km per hour (192 kps)!

With our Saturn VIIIA we will assume we have developed a high power Nuclear Thermal Rocket with an Isp of 1000 sec- or about 10% more than our baseline used with the Saturn VIIA. With our mass ratio of 20 this Isp will get us a total Δv of about 30kps. Instead of using Venus or Mercury to get closer to the sun, it will be easier and less stressful for our spacecraft to spend most of its time in deeper space and use Jupiter to do a retrograde powered maneuver to drop our starship toward the sun. Let's use 10kps of our rocket thrust to go into an elliptical orbit with a perigee that approaches Jupiter. Once at Jupiter, we would apply a small (about 1kps) burn but this time, instead of performing the maneuver behind Jupiter and using Jupiter gravitational field to swing faster out of the Solar System, we approach from in front of Jupiter and use the reverse gravitational slingshot, and a small 1kps powered maneuver, to do a retrograde burn and eliminate virtually all our orbital speed so that we now drop down toward the sun with a perigee target of 10 solar radii. At the sun we do a second burn and use all our fuel for a powered maneuver. If we apply our full 20kps at the lowest portion of the orbit, using the graph in chapter 2, we will escape the solar system at an astounding 90 kps. Since we are further away from the sun in radii than we were at Jupiter, and since the sun is so much more massive, we will make a legitimate but rough assumption that we can perform a much longer burn than the 15 minutes we gave ourselves at Jupiter- we will now use a target of two hours.

If we target a 20 kps burn at the sun how much fuel would we need? Using our Equation 3-3 and rearranging we come up with the following equation:

$$\text{Equation 8-1 } \ln\left(\frac{m_0}{m_1}\right) = \frac{\Delta V}{v_e}$$

$$\text{EQUATION 8-2 } \frac{m_0}{m_1} = e^{\frac{\Delta V}{v_e}}$$

$$\text{EQUATION 8-3 } m_0 = m_1 e^{\frac{\Delta V}{v_e}}$$

$$m_0 = m_1 e^{\frac{\Delta V}{v_e}} = 150,000(e^{\frac{20}{9.81}})$$

$$m_0 = 1,154,514 \text{ kg}$$

We will have to consume this amount of fuel in our 7200 seconds (2hr) Oberth maneuver window. This means we need to consume 154 kg/s. Our original engine considered with the Saturn VII we expelled 130kg per second so we could do our burn in the required two hours. If we either built a larger rocket or if we had two engines equivalent with the 130kg/sec fuel consumption, we could do our burn in a little more than an hour and get a slightly higher performance. In this case our MR is about 7.68.

With an escape velocity of 90kps we are traveling over 5x faster than the Voyager 1's exit velocity of about 17kps. Not bad!

Solar Heating During an Aggressive Powered Maneuver

A natural question that comes to mind is can we approach this close (or even closer) to the sun and survive? I believe the answer to this is that it will be challenging but doable. We will have to protect our spacecraft from both the tremendous heat, as well as the intensely radioactive environment. One aspect working in our favor is that our tremendous speeds we will be in the most intense region during the closest approach for a short period of time. The solar parker probe will approach the sun within 6.9 million km (10 solar radii) beginning in 2025. At that distance the spacecraft will be traveling at nearly 200kps. In one hour, it will have traveled 720,000 km. Of course, this velocity occurs only at the closest approach, but the speed will still be substantial, and the Parker Solar Probe, along with our starship would spend a little more than two weeks within the orbit of Mercury. This is fortunate because for our starship our hydrogen tanks will need to be kept cool enough on the solar approach to remain liquid. This is not a concern as we leave the sun because after our powered maneuver, we should have no fuel remaining so our tank could be discarded.

With redundancy and shielding of our most sensitive electronics, the Parker Solar probe is proving that instrumentation can be designed to survive multiple close approaches to the sun. Similarly, if we were to have a manned spacecraft additional precaution would have to be taken. During the few days of closet approach, it will be necessary to have all the crew shelter in a solar storm shelter that would have enhanced insulated from solar radiation with several meters of water or some equally effective radiation shielding material.

Before we move on let us consider a truly aggressive Oberth maneuver those approaches within three solar radii. Would this even be possible? What would our starships performance be?

Using the same formula and approach as in Chapter 2, I plotted a new performance graph that includes both the original calculations with an approach within 10 Solar Radii and added a new approach that would approach within three solar radii (or one diameter of the sun's surface. We can see from this graph that our final dV would be on the order of 120 kps if we applied a 20kps dV.

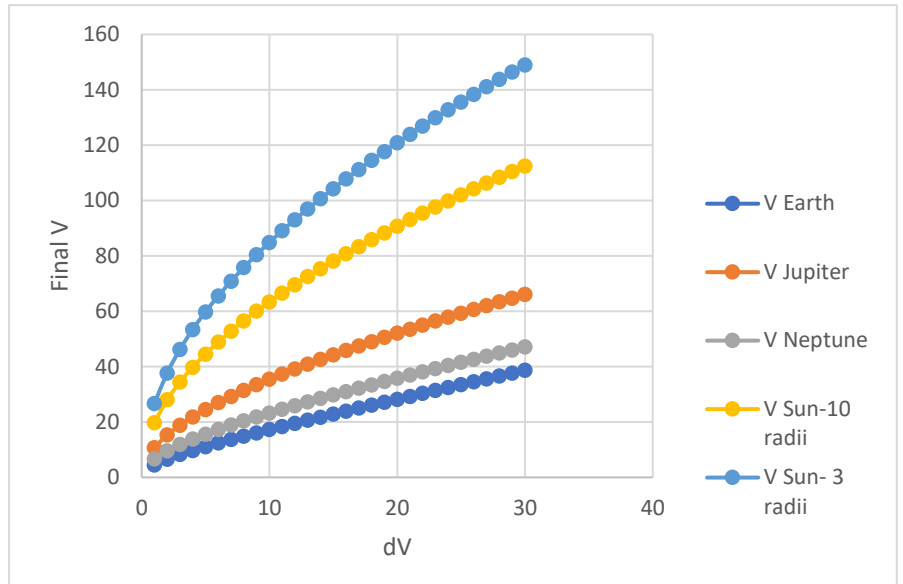


FIGURE 8-3 AGGRESSIVE POWERED MANEUVER AT 3 SOLAR RADII

The engineering challenges of a close approach are substantial- would this be possible?

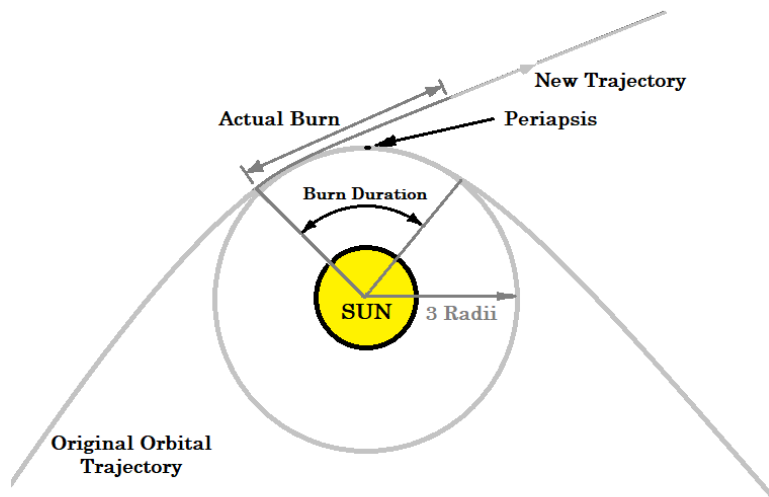


FIGURE 8-4 3 RADII POWERED MANEUVER

First, even at one solar diameter from the sun space is still a vacuum. As Figure 8-4 and 8-5 show, even below the sun's visible surface, the density is below that of air in your room- indeed at the visible surface it is about 1/1000th as low as the earth's atmosphere is at sea level- or about 10⁻⁶ g/cm³. Air at sea level is about 10⁻³ g/cm³ so for all practical purposes this is near a vacuum. Above this it continues to drop off steeply such that about 2500 km above the visible surface is approximately 10⁻¹⁷ g/cm³. Despite this, the tenuous atmosphere, such as it exists, would be extremely damaging if a spacecraft were it to

linger for too long as it is filled with very energetic ions (and a huge flux of photons!). Adding to this, our ship will be traveling through these ions well in excess of 400kps at the apogee. Direct thermal radiation would be intense. As we draw closer to the sun we are nevertheless in the solar atmosphere even if it is tenuous. This means that even if the spacecraft is behind a shadow shield, the side in "shadow" will still see some thermal heat radiating from the solar atmosphere, reducing some the of the cooling capabilities of the spacecraft.

Using the approximate solar energy flux of 1370 W/m^2 at the earth's orbit, how much energy would fall on each meter at 10 radii and 3 radii from the center of the sun? The earth is about 150,000,000 km from the sun. Ten Radii would be about 6,900,000 or a little less than $1/22^{\text{nd}}$ the distance. This means

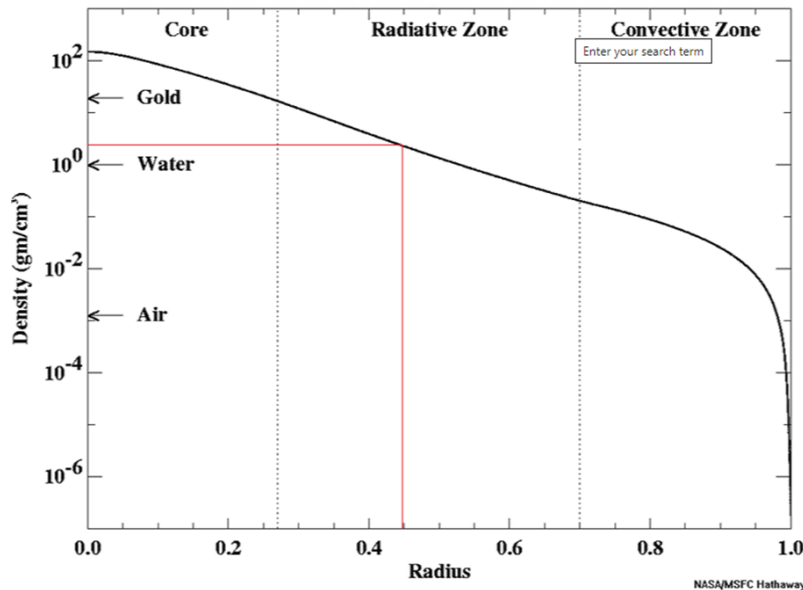


FIGURE 8-5 SUNS DENSITY PROFILE (SOLAR PHYSICS- THE SOLAR INTERIOR, N.D.)

that the radiation load would be nearly 472 times higher- or almost 650,000 watts per meter². At three radii, or about 2,100,000 km we would be 71.5 times closer, with a heat load 5100 times more than at the earth- or 7,100,000 watts per meter. A typical thermal protection system for atmospheric reentry is usually capable of handling about 2,300,000 watts per meter primarily through ablation which may not be applicable to our example. It does show that for short periods of time, technologies have been developed that can handle extremely high heat loads. Furthermore, our heat loads will be substantially less if we have a highly reflective surface. This is not

helpful on a typical thermal protection system used for reentry as their heating is mostly caused by compression of the atmosphere in front of the spacecraft. The violent compression of the atmosphere creates tremendous heat and will then heat the spacecraft surface due to radiation and convection.

In a mission like this I foresee a couple of options. One possible solution is to build extremely lightweight thermal tile like material that

would serve as a shield between the sun and our spacecraft- similar to what was done with the Parker Solar Probe. Another alternative might be to have a transpiration cooling whereby a fluid- perhaps water, is injected through small holes or pores in the sun shield. The water carries away some of the heat via evaporative cooling. Another alternative would be the construction of a highly reflective, lightweight exterior shell behind which our

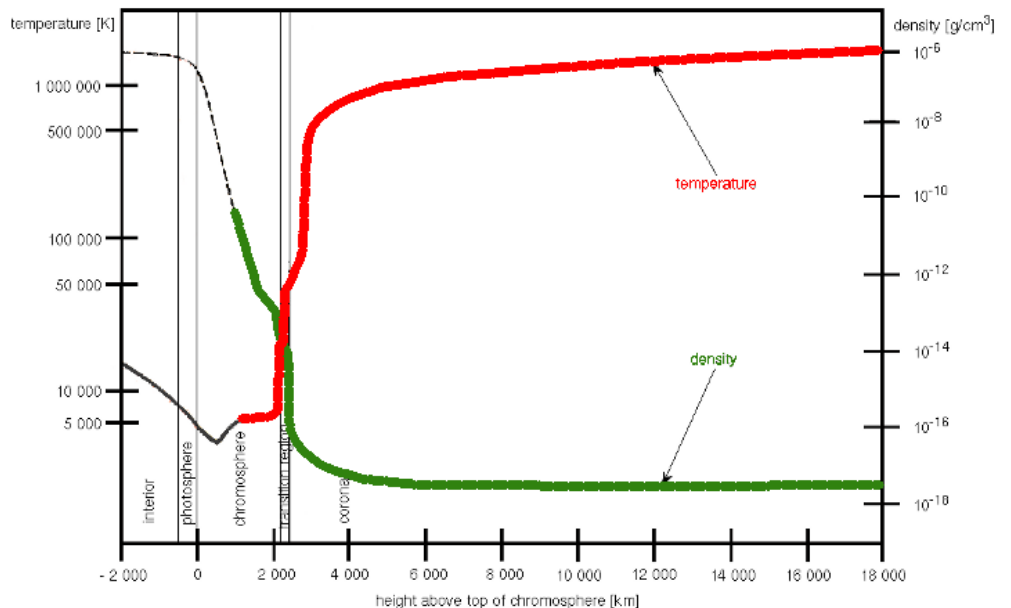


FIGURE 8-6 SOLAR ATMOSPHERE (EDDY, 1979)

rocket would hide- similar to the James Webb space telescopes (JWST), where several thin layers provide progressively higher levels of temperature reduction. The JWST solution would require considerably more engineering research as the thermal loads on our solar swing bye are over 5000 times



FIGURE 8-7 JAMES WEBB SUNSHIELD

more extreme than what the JWST has to experience. The JWST five layers reduced the heat by about 570C- nowhere near sufficient for our requirements.

Furthermore, our spacecraft is much larger and therefore more challenging to shield. Nevertheless, my initial feeling is that this option may be lighter than the first two options. A fourth option that could be done in conjunction with any of the other options would be active cooling of either the ship or the shield. The hydrogen tanks could be continuously cooled through radiator panels (the

panels would be in the shadow of our sun shield) or some sort of transpiration cooling, where hydrogen (or water or whatever other material is selected) is allowed to boil off and carry some of the heat off. Regardless, the engineering challenges of such a cooling requirement are formidable and a lot of engineering experimentation would need to be done to create a cooling system and the materials that are light weight, highly reflective and able to survive for the several days or so in an extremely high thermal radiation environment.

How hot would an object get if positioned 3 solar radii from the sun's center? First, we need to understand a bit about heat transfer. Objects can either be heated or cooled through convection or radiation or both. Convection is the most effective method. Convection occurs when a hot object is in contact with a cooler object and transfers its energy to the cooler object. This can be transferred to either an atmosphere (air) or a liquid (water) or another solid. In the vacuum of space convection cannot occur and all cooling is radiative.

So how hot would an object be if it was placed directly in the sun's rays at 3 Radii?

The luminosity of the sun is described by the equation:

$$\text{EQUATION 8-4 } L_{\odot} = 4\pi R_{\odot}^2 \sigma T_{\odot}^4$$

$L_{\odot}$ is the suns luminosity.

Cross-Section of Webb's Five-Layer Sunshield

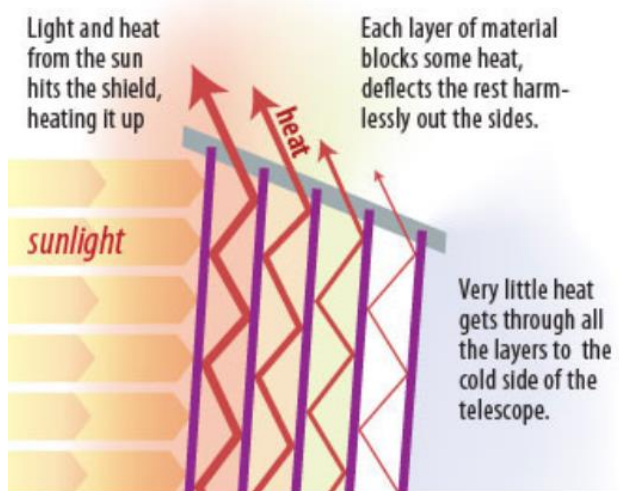


FIGURE 8-8 JWST FIVE LAYER SUNSHIELD (COURTESY NASA)

σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$)

R_0 is the radius of the sun in meters. This is $696 \times 10^6 \text{ m}$

T_0 is the temperature of the sun in Kelvin. The surface temperature of the sun at R_0 is 5780K

To determine the temperature at a different distance from the sun we can use the equation:

EQUATION 8-5 $T_T^4 = \left(\frac{R_0^2 T_0^4}{4R_T^2} \right)$

Where T_T = temperature of our Target and R_T is the radial distance to our target.

Rearranging and simplifying:

EQUATION 8-6 $T_T = T_0 \sqrt{\left(\frac{R_0}{2R_T} \right)}$

$$T_T = 5780K \sqrt{\left(\frac{6.96 \times 10^8}{2 * 2.088 \times 10^9} \right)}$$

$$T_T = 2360K$$

Quite a high temperature and more than virtually any material can handle. Fortunately, this assumes that all the radiation is absorbed. In reality if we have a highly reflective surface this T will be substantially reduced. Assume we have an albedo of .95 (95% of the energy is reflected)- now only 5% is absorbed. This reduces our temperature by $(.05)^{.25} = .479$. Our new temperature is now 1130K. Still quite hot but more manageable.

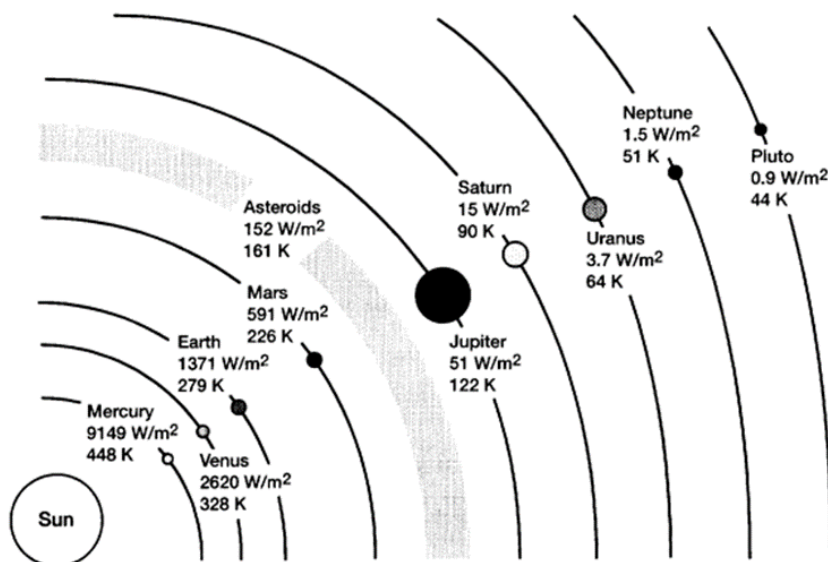


Figure 2.—Solar heat flux and spacecraft surface temperatures at various planetary orbit distances.

FIGURE 8-9 SOLAR HEAT FLUX AT VARIOUS PLANET ORBITS (JUHASZ, 2001, p. 9)

Finally, I want to revisit a LH/LOX chemical rocket design like we considered at the end of Chapter 6 and use it on a similar mission profile to our Saturn VIIIA. In this version we land a nuclear power plant, a series of large hydrogen and oxygen tanks and some SSME's on a water rich asteroid, Ort cloud or Kuiper belt object. As with the first version, the reactors' power would be used to first melt some ice, then separate the water and hydrogen through the straightforward process of electrolysis and begin filling up the hydrogen and oxygen

tanks. Now, instead of accelerating the rocket out of the Solar System you decelerate the object so that

it drops toward the sun so you can take advantage of an Oberth maneuver. Kuiper belt and Oort cloud objects are so distant from the sun that their velocities are frequently only 1-2 kps or so. However, since they are so distant, they have tremendous potential energy. By literally stopping the object you can take advantage of this energy with the powered maneuver. As with our Saturn VIIIA example, our target distance from the center of the sun is only 3 solar radii. As we saw, a 20kps dv as our target will give us our 120kps escape velocity. As with the nuclear rocket example we will restrict ourselves to a 120 min burn time. It should be noted that the SSME were not designed to burn for two hours straight. I am not sure the best approach, but it may pay to have a large number of “spare” engines where an engine fires for 20 minutes or so and then shut down and then the backup engines would fire and so on until you reached your two hour burn time.

Since each engine uses about 515 kg/s of Hydrogen and Oxygen, in 120 minutes you would consume about 3,708,000 kg, or 3,708mt of reaction mass for each engine.

Applying a target dv of 20kps, with an specific impulse of 460 rearranging the terms of Equation 8-2:

EQUATION 8-7 $\frac{m_0}{m_1} = e^{\frac{\Delta V}{v_e}}$

Because of the low exhaust velocity of a chemical engine (less than half that of the nuclear engine), we will need a much larger mass ratio than needed for Nuclear Thermal.

$$\frac{m_0}{m_1} = e^{\frac{\Delta V}{v_e}} = e^{\frac{20}{4.45}} = 90$$

If we assume our empty m1 mass is 150 mt, our initial mass will be 13,500 mt of which our fuel is 13,350mt. Based on the fact that our engines consume about 3,708mt each during the two-hour burn, this equates to about 3.64 engines firing for the full two hours. Assuming we run four engines, it means we will either use all our fuel faster and can reduce our burn time, or we can derate the engines... which perhaps will allow them to operate for a very long time. Optimistically I will assume that the derated engines can last an hour each, we will therefore need 8 engines total. Our engines weigh about 3.2 mt each so our eight engines would come in at about 25.6 mt leaving the remaining mass for our power supply and empty fuel and oxygen tanks. Our change in velocity, using only chemical engines with this aggressive 3 radii Oberth maneuver would be the same as our Nuclear Engine option, or 120kps. This is a tremendous performance and all from a Chemical Engine and may make the Chemical Engine competitive with Nuclear Thermal in some scenarios.

What can we take from this? The good news is that even with Chemical rockets and a less aggressive power maneuver that approached within 10 solar radii, our exit velocity would be about 90kps which would reduce our time to travel 10 LY down to about 33 thousand years. Furthermore, using either the nuclear option or chemical option along with a powered maneuver is very scalable. We could see a starship ten times larger than what we just discussed- and because both the nuclear rocket and chemical rockets are fairly light and compact, we can easily conceive just using 10x more engines... As a final point to keep in mind is that the Starship powered by the nuclear engine with the same final weight as a chemically powered rocket, will have a much smaller starting mass- in our examples the chemical rocket mass ratio was approximately 90 while the nuclear starship was about 7.7. This means that the nuclear rocket needs much less thrust to achieve the same Δv as the chemical.

Technology- Solar Thermal

I wanted to take a few moments and discuss Solar Thermal. Solar thermal has the ability to generate temperatures as high as a Nuclear Thermal and has been looked at by NASA in various studies (Gerrish, 2016). As its name suggests, it would take its energy from the sun which limits it to the inner solar system. If the thrust and therefore acceleration is high enough, a few hours of propulsion is all you need to exit the Solar System at high velocity.

Solar thermal has many of the same challenges as Nuclear (or for that matter chemical) thermal rockets. Specific Impulse for Nuclear and Chemical rockets are fundamentally driven by the temperature of the reaction mass medium. The Solar Thermal rocket has the ability to heat a reaction mass to temperatures as high as the most advanced nuclear engine. Unfortunately, we do not have materials that can be heated to unlimited temperatures- so ultimately, Solar Thermal specific impulses will peak at about the same as the nuclear engine- 900 to 1000 seconds so while we can make the fuel/reaction mass hotter, we can't make the expansion chamber take the higher temperatures that a higher specific impulse rocket would require.

One area that could be researched borrows an idea of pulsed propulsion. Perhaps a small kg sized packet of fuel can be ejected out the back of the rocket and then exposed to the tremendous heat from large solar mirrors. When the packet is hit by the intense radiation focused by the Solar Thermal mirrors, it would violently vaporize, and provide a pulse to a pusher plate. Whether this would be feasible or perform any better than a 1000 second specific rocket would require considerable design and analysis.

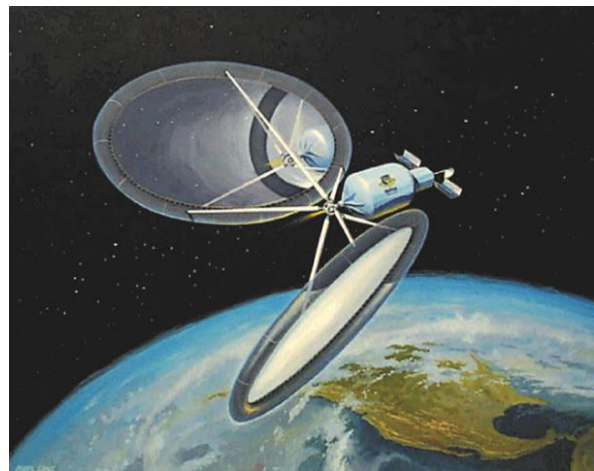


FIGURE 8-10 SOLAR THERMAL ROCKET

Technology- Power- Fission Reactors

With the various electrical thrusters we have considered, an adequate power source remains a major limiting factor. In prior chapters, we demonstrated how Plutonium or Americium RTGs, and even Stirling generators produce far too little power for many of our thruster options.

RTGs which have no moving parts are extremely reliable but are very inefficient. Next up in efficiency are the Plutonium or Americium fueled Stirling Generators. While up to four times more efficient with their fuel, they still are relatively small in size and use relatively rare Plutonium and Americium. Furthermore, reciprocating Stirling Generators are mechanical and have not demonstrated a high duration (many years) of operation.

The next step up in power but needing considerable engineering design work to make flight ready would be a true fission reactor. Fission reactors are normally powered by Uranium, but like the ASGR, fission reactors have a mechanical component in which the heat from the fission reactor would either power a Stirling Generator (as with KRUSTY) or spin a turbine that would turn a generator to generate electricity.

Fission reactors operate very differently from an RTG. RTG power is generated by the spontaneous decay of Plutonium or Americium which releases heat. Fission reactors also use radioactive decay but

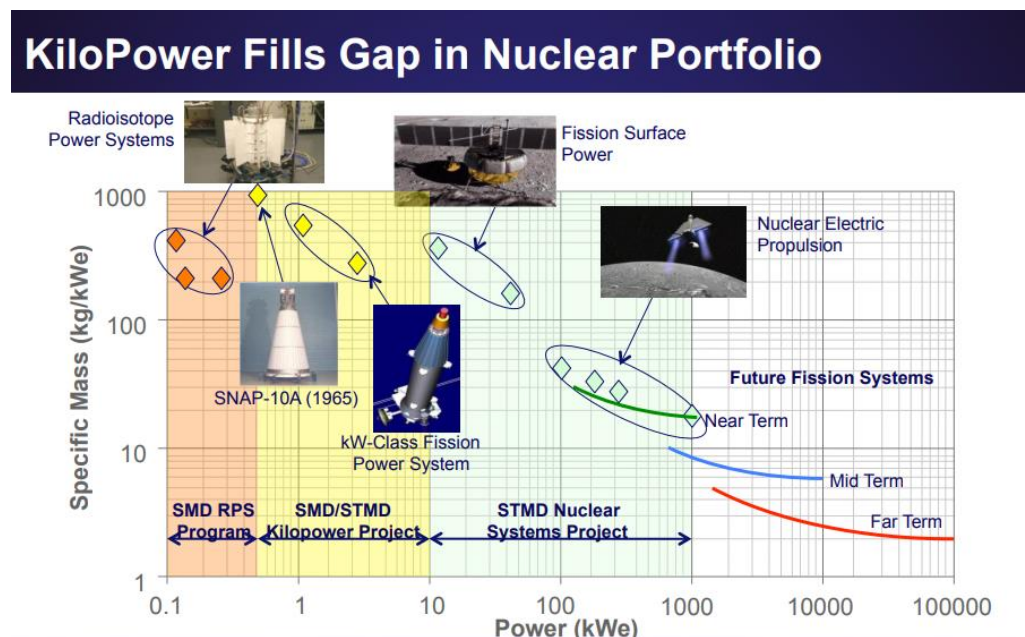


FIGURE 8-11 KRUSTY- KILOPOWER FILLS THE GAP (COURTESY OF NASA)

with fission the decay of one atom of Uranium initiates the splitting of another atom and so on in a fission chain reaction. The relative abundance of Uranium, as well as the large amount of energy generated by having a controlled chain

reaction, permits the construction of very high power and large reactors. Large Nuclear complexes on earth frequently generate 1GW_e (where the small e means electrical power).

In Figure 7-4 we showed various power generating options, how much power they generate and the mass efficiency- how much kg per an amount of electric watts. KRUSTY was designed to generate about 6.67W/kg . Figure 8-10 shows the inverse of this- kg/kWe . In Figure 8-11 KRUSTY would be about 150kg/kWe .

Uranium is a naturally occurring and longer lasting fuel than Plutonium and comes in two primary isotopes- ^{235}U and ^{238}U . The most common is ^{238}U which has a half-life of 4.47 billion years and makes up nearly 99% of Uranium. The next most common isotope is ^{235}U which has a half-life of 704million years and is present at a concentration of about .72%. ^{238}U is non-fissile which means

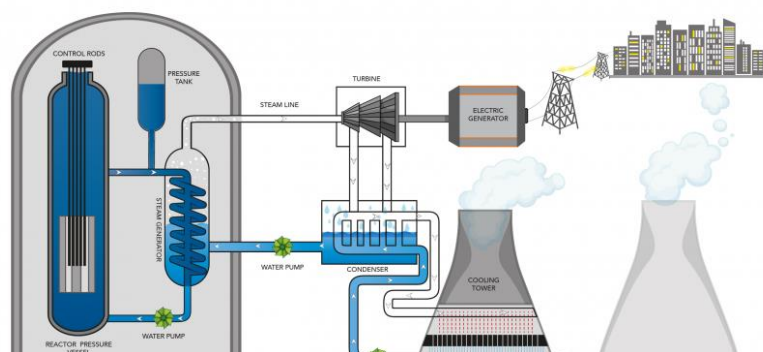


FIGURE 8-12 PRESSURIZED LIGHT WATER REACTOR (OFFICE OF NUCLEAR ENERGY, N.D.)

that it cannot support a chain reaction with itself- the neutrons it releases during its decay are not energetic enough. ^{238}U can fission, but only with fast neutrons. ^{235}U is fissile and can support a chain reaction by itself.

Most reactors are called light water reactors (Figure 8-11) and require Uranium enrichment-whereby the proportion of ^{235}U is raised, typically to concentrations of 3.5%-4.5%. Highly Enriched Uranium (HEU) is where we have a 20% or higher concentration of ^{235}U . Very high enrichment is called Weapons Grade and usually has 85% ^{235}U and, as the name suggests, can be used to build nuclear bombs. Using enriched fuel in a reactor (especially smaller reactors on ships and submarines) can increase the time between nuclear fuel changeout and permits a smaller reactor.

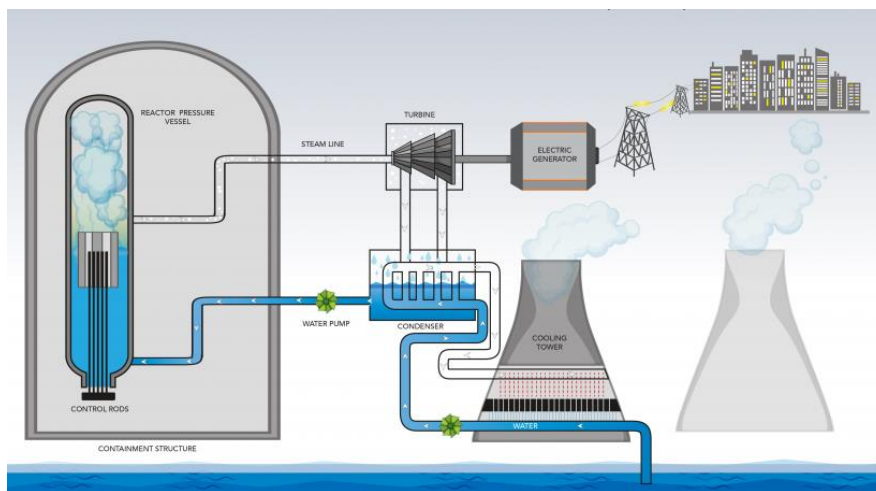


FIGURE 8-13 BOILING WATER REACTOR (OFFICE OF NUCLEAR ENERGY, N.D.)

about 150kWe/kg.

The KRUSTY program considered designs up to 10kWe of power. Similar to the previously discussed Stirling designs, KRUSTY incorporated a Stirling engine but instead of using Plutonium or Americium for power, used enriched Uranium as the fuel. With our target 150 mt empty mass starship, let us assume we use half of our weight (75,000 kg) for power. Using KRUSTY's 6.67 watts per kg, our reactor would be able to generate 500kw. As originally conceived, the largest KRUSTY reactor would generate only 10kw so if we wanted to generate 500kw of power we would need over 50 of the largest generators being considered- likely not an optimum solution. We can assume that some descendent of would both be able to generate larger amounts of power and reduce its weight per watt to 10W per kg. A 75mt reactor would then generate 750kW. How much Uranium would be needed to power this reactor? KRUSTY target was to generate 44,000 watts thermal from 44kg of enriched Uranium. This provides about 10,000 watts of electricity so KRUSTY generates about 227 watts per kg. Furthermore, KRUSTY was designed to last for 12-15 years. This works out to only about 3kg per year of Uranium to generate 10kw.

There has been some design work on space fission reactors in the United States. KRUSTY (Kilopower Reactor Using Stirling Technology) was one of the first significant design attempts at building a working space reactor. KRUSTY was designed to generate about 6.67W/kg. Figure 8-11 shows the inverse of this- kg/kWe. On this chart KRUSTY would be

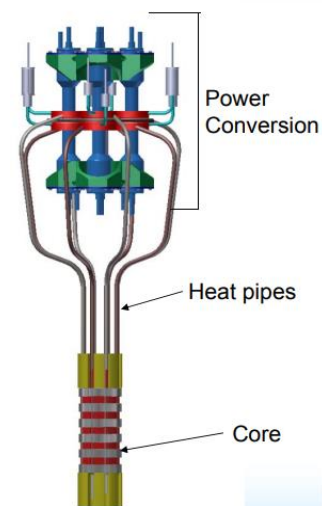


FIGURE 8-14 KRUSTY- THE POWER CONVERSION PORTION CONSISTS OF STERLING GENERATORS (COURTESY NASA)

Depending on the exact design of the reactor and whether or not it uses enriched or highly enriched Uranium, will determine how much fuel is used. In the prior chapter (Figure 7-3) I extrapolated a very advanced, reliable, and lightweight fission reactor which I called Advance Space Nuclear (ASN). I assumed that it was a much more powerful reactor than KRUSTY- possibly using Stirling Generators but more likely some sort of turbine powered reactor as is used on earth for nuclear power plants. Its fuel efficiency (watts generated per kg of fuel) is close to that of KRUSTY, but I assume that the larger size may permit some mass efficiencies. To get this sort of performance this sort of plant may need to use Highly Enriched Uranium. Note also that beginning with the ASN I assume one watt of electricity per three watts of thermal. This appears to be the efficiency for very large domestic nuclear power plants.

The US Navy operates many compact nuclear reactors on its Aircraft Carriers and Submarines. These power plants are pressurized water reactors but do not have the need for a cooling tower- ocean water serves this purpose. As a general design principle, higher enrichment allows for a more compact design and are longer lasting before requiring refueling- new reactor cores on navy ships are designed to last for over 30 years. It is possible to build a non-enriched reactors called Pressurized heavy water reactors. An example of this is the Canadian facility called Canadian Deuterium Uranium (CANDU) nuclear reactor which uses only natural Uranium fuel. These reactors need to use Heavy Water (water where at least one of its hydrogen atoms being Deuterium) as a moderator vs normal water. Heavy water does not absorb neutrons as effectively as a light water reactor, leaving more neutrons available to hit the rare ^{235}U . Heavy Water requires separation and processing as only about 1 out of 3200 water molecules are Heavy Water. Disadvantages of these reactors is the need to use heavy water and a larger amount of uranium needed (since the power still comes from the ^{235}U) and hence the amount of fuel per unit of power produced is much more than an enriched reactor. Since they use more uranium but have less ^{235}U they need to be refueled more frequently and as a result generate more waste.

All reactors require fresh fuel. Over time a light water's ^{235}U is burned up and less power is generated while more and more impurities build up in the reactor vessel until the reactor can no longer support fission. In a civilian reactor, so that the power plant does not have to be totally shut down, typically about 1/3 of the reactor core is replaced every 12-24 months which means that the average time a nuclear fuel assembly produces usable power is for 4-6 years. Regardless of the eventual fission design chosen, periodically we will need to have the spent fuel be replaced with fresh fuel. We should be able to reprocess some of the spent fuel to get more life. In a typical nuclear power plant only about 4% of the ^{235}U is burned up when the fuel is pulled out. For long term spaceflight some sort of reprocessing, along with fresh ^{235}U will be required to refuel our power plant. Since ^{235}U has a half-life of 703.8 million years the fresh fuel would need to be isolated so as not to undergo a chain reaction before it is needed. If the starship has a highly enriched reactor similar to a military reactor for a mission of 1000 years, you will need approximately 30 swap outs of fuel. If we have reprocessing capabilities, we may be able to substantially reduce this.

In Table 7-3 for the Advanced Space Nuclear (ASN) I projected a larger version of KRUSTY but with some improvements to reduce its mass. Civilian power plants do not use Highly Enriched Uranium, but usually only Enriched Uranium. Using a typical civilian power plant fuel, I also extrapolated a power plant that more closely mirrored those of a large earth-based reactor and named it Super Space Nuclear. This reactor would use more fuel but less enriched fuel. To get an idea of the amount of fuel needed, let us assume we need 1MW_e of power. Per Table 7-3 a one 1MW_e version of the SSN would, using our rules of thumb that to generate 1MW_e for one year we would go through 250kg of fuel. In our prior example

of using an Electric Thruster, we would need to generate 1MW_e for 164 years. This means we would need 41mt of fuel. Again using our other rule of thumb of a reactor being able to generate 10W/kg, we would need a reactor that weighs 100mt. Total mass of fuel and reactor(s) would be 141mt. This is eminently doable. If we needed this power for 10,000 years the mass becomes more prohibitive- 2500mt of fuel for a total of 2600mt. One way around this is to use highly enriched uranium, which depending on the enrichment, may only use only ¼ of the Uranium mass. A better solution regardless of whether we used enriched or highly enriched fuel would be to have some sort of reprocessing capabilities to permit reuse of the spent Uranium.

One final area to look at is to look at what drives our 100mt reactor mass? Besides the weight of the nuclear fuel, the containment vessel, the Stirling Engines or turbines, and all the associated hardware, a big source of mass is driven by the need to cool the working fluid (usually steam) before it gets reheated back in the reactor. As mentioned earlier in this chapter, cooling is surprisingly difficult in space. On earth large and massive cooling towers are used that use conduction to get rid of the heat. In space, with our limited payload mass, and the fact that we don't have a river or ocean to conduct our heat to, this is not an option. We can only count on radiation for cooling.

To get a rough idea of how big of a surface area is required to remove heat we need to use the Stefan-Boltzmann Law that we introduced earlier in this chapter:

EQUATION 8-8 $\Phi_e = A_i \epsilon \sigma (T_{rad}^4 - T_{sink}^4)$

Where:

Φ_e = the radiant power

A_i is the radiator surface area

ϵ is the emissivity/absorptivity and is the effectiveness of the material at emitting electromagnetic radiation. For most materials it is between .8 and 1 (1 being a perfect blackbody)

T_{rad} is the radiator temperature. This is a great simplification and a thorough analysis would need to be developed. The most effective radiators would have fluid lines running up and down a panel. The radiator temperature, for now, could be assumed to be the temperature of the fluid.

T_{sink} is the effective sink temperature. In deep space this is 2.7 degrees. Near a star it will be much greater- unless in a shadow behind a screen.

Suppose we wanted to calculate the surface area required to get rid of 1 MW of power? Rearranging our terms:

EQUATION 8-9 $A_i = \frac{\Phi_e}{\epsilon \sigma (T_{rad}^4 - T_{sink}^4)}$

Where:

Φ_e = Assume that to generate 1 MWe we will have a 3MW_{th} (assume that we need to get rid of this much heat)

ϵ = .9

T_{rad} = 423k (150C)

$T_{\text{sink}} = 20\text{K}$. We will assume we are very far out in space. Note from Figure 8-8 this would equate to a distance far outside of the orbit of Pluto. (Juhasz, 2001)

σ_{sb} is a derived constant = $5.67 \times 10^{-8} \text{ Wm}^2\text{K}^4$

We will assume a radiator temperature of 150 C (423K). Filling in our equation we would get:

$$A_i = \frac{3,000,000}{.9(5.67 \times 10^{-8})(423^4 - 20^4)} = 1836 \text{ m}^2 \text{ or a square about 42.9 m on a side.}$$

Note, as with many things about designing our starship, determining the optimum temperature of the radiator will require design trade-offs and 150C may be too high. If a circulating fluid like water were being pumped through thousands of meters of pipe to help radiate the heat, its starting temperature is more than 150C and its final temperature below which will make heat radiation calculations more complicated. I am not sure if an average of 150F is reasonable. Let's assume that the water starts at 175C. To keep water in its liquid phase at 175F we would need to keep the pressure at over 9 bar - requiring moderately thick (and heavy) wall piping. This is certainly not a showstopper as hydraulic systems on aircraft typically operate at 15-25 bar, but it does mean that the system is at high pressure and even a small leak can release a lot of cooling water quickly. The Radiator size will likely be a large contributor to our 10 watts per kg mass. Note also that this size would need to be larger if we were trying to cool our ship nearer the sun- in this case our T_{sink} temperature would be much higher (unless effectively insulated from the solar radiation) and care would have to be taken to have the radiators at a shallow angle to the incident sunlight or behind an effective heat shield. The heat Sink temperature for a flat plate at the earth's orbit (1 AU from the sun) would be 279K (Presby, 2004).

Finally, keep in mind that part of our reactor mass is radiation shielding. If shielding can be lowered, perhaps by positioning the reactors far away from occupied parts of the ship, we may be able to have a relatively low shielding mass.

To conclude our power analysis, we can see that fission reactors can generate the required power for a prolonged period of time. Based on prior engineering work and some reasonable extrapolation of capabilities that build upon the KRUSTY goal we can assume development of a powerplant called Advanced Space Nuclear (ASN) that puts out 10W/kg.

Saturn VIIIB- Electrical Thrusters Improved

In Chapter VII we saw that there are many viable options for electric thrusters. The constraining factors preventing their adoption are:

- High Power requirements
- Low Thrust
- Traditionally limited to Noble gasses for fuel (Xenon and Argon)

In the previous section we speculated on the development of the ASN reactor putting out 10 W_e/kg . Looking back at the options shown in table 7.2 we have three more electric thruster types available. All of them can provide more thrust, and more Isp but require much more power. Indeed, from a mass

perspective, the HiPEP would be the best candidate. However, its power requirements are very high. On the other hand, the VASIMR and MPD have slightly lower specific impulse but much higher thrusts. Furthermore, these engines can use alternate elements for fuel. In the case of the VASIMR design, atoms do not come in contact with grids or electrodes so using alternative atoms like Hydrogen should not cause electrode erosion. In addition, using lighter elements will increase the specific impulse so it is conceivable that VASIMR or the MPDT can reach 10000 sec specific impulse.

Regardless of the electric thruster selected, to get more thrust and higher Specific impulse we will need to have at least 200kW of power, far more than even our Radioisotopes Stirling generator can provide. The large fission power plants, with their increased watt per kg efficiency, gives us this. More power may lead to higher specific impulses but more frequently they lead to higher thrust which will significantly reduce the time needed to accelerate or provide for a much more massive spacecraft.

The first challenge is that none of these higher performing engines- HiPEP, MPDT nor VASIMR have ever been tested in space. In the case of VASIMR this is a major issue as some critics have charged that the design is fundamentally flawed. However, the VASIMR does have a fairly long test history on earth, and we could use this to develop our next round of Starships and VASIMR in particular provides a relatively high thrust and fuel flow.

Our Saturn VIII would have had several more decades of engineering work to perfect one or more of these Electric thruster engines. For now, we let us an engine with VASIMR like specifications.

Isp= 5000sec

Power Requirement- 200kw

Thrust= 5.4 N

$$v_e = g_o I_{sp} = v_e = 9.81 * 5000 = 49,050mps$$

$$F = ma$$

$$a = \frac{F}{m} = \frac{5.4}{3,000,000} = 1.67 \times 10^{-6}$$

This is only the velocity at the beginning. As the rocket ejects mass and gets lighter, the acceleration would increase. Regardless, we need to calculate how much mass is ejected per second. Using our equation 7-2:

$$\dot{m} = \frac{F_{Thrust}}{v_e} = \frac{5.4}{49050}$$

$$\dot{m} = 1.1 \times 10^{-4} \text{ kg/sec}$$

To consume the 2,850,000 kg of propellant:

$$\text{EQUATION 8-10 } t = \frac{(m_0 - m_1)}{\dot{m}}$$

$$t = \frac{(3,000,000 - 150,000)}{1.1 \times 10^{-4}} = 25,909,090,909 \text{ sec}$$

Or 822 years of acceleration

At the end of this period our velocity would be:

$$\Delta V = v_e \ln \left(\frac{m_0}{m_1} \right) = 49,050 \ln(20) = 146,941 \text{mps} = 147 \text{kps}$$

This is a sizeable velocity- much higher than our chemical or nuclear rockets were able to achieve. This is about 60 kps faster than our Nuclear Thermal. But even with this sizeable velocity, the fact that it takes 822 years of accelerations to get up to full speed is a large negative! Compare this to our Nuclear Thermal - our Nuclear Starship while performing after its journey to Jupiter with a retrograde maneuver to drop toward the sun and finally a powered maneuver at 10 radii around the sun should be able to get to its 60kps within a couple of hours.

One easy way of improving performance with the VASIMR is to use 5 engines instead of one. Our thrust will now be 5x greater as will our acceleration. Thrust will be 27 newtons and we would consume all of its reaction mass in 1/5th the time- or 164 years. This is a substantial performance improvement but comes with many challenges of which the biggest is building a power supply of 1MW and have it last for 164 years.

We could still perform a gravitational slingshot around Jupiter to alter our trajectory and, as long as our target star is within a few degrees of the elliptic gain either some additional dV or at least alter our trajectory. As noted previously, not many stars of interest are near the elliptic so to be consistent with our Nuclear Rocket, we will only add 3kps for a gravitational slingshot since the target star is likely to be far away from the orbital plane and the possible gain will be quite small- we will settle on a final speed of 150kps.

One additional complexity with the ion engine has been mentioned before- that its actual velocity performance would be far less than 147kps because of its low thrust and high gravity losses. Any electric thrust starship will need some sort of high thrust first stage to exit the solar system. Only then, when the spaceship is exiting at perhaps 20kps will it be appropriate to turn on the ion engines.

For our nominal Saturn VIIB ship requiring 200kW_e of power, our reactor mass would equate to about 20mt- but assuming some power margin as well as additional power for our instruments and payload we would assume needing 250kW_e and 25 mt mass. If we wanted a 1 MW power plant, we would mass 100mt (or most of our allocated m1 of 150mt). This would not include the replacement core fuel. Because of the m1 mass limit we will restrict our power needs to 250kW_e, and limit our Saturn VIII to a VASIMR sized engine of 5.7nt. We determined that it would need to accelerate for 822 years to get up to speed. If we wanted to bring along replacement fuel (required, every few decades of operation) we could develop some rules of thumb. With the 250kwe ASN we assume a fuel changeout every 15 years of 1mt. Over the 822 years we would need about 55 swap outs for a total fuel mass of 55mt. Adding this mass to our power supply we will have slightly more than 80mt required for power plant.

This seems feasible and keeps us within our 150mt target mass. Fuel mass can be further reduced by additional enrichment of the fuel as is done with naval ships which can last for 30+ years between refueling. Furthermore, in future Chapters we will consider more efficient power plants that generate 20W_e/kg.

Despite their low thrust and high-power demands, Ion engines and their related electric thruster engines are a well-known engineering design and we can feel comfortable that we can wring even more performance from them over the next few decades.

Saturn VIIC- Two Stage Hybrid

With the Saturn VIIC we had a two-stage solution using a Nuclear Thermal and an Ion engine. In this chapter, we will add the additional capabilities of an improved Nuclear Thermal, combined with an aggressive powered maneuver by the sun, and incremental improvements to our nuclear power plant.

As shown in the previous chapter, a two-stage configuration, while improving on our performance, leaves a very small payload available. Nevertheless, with the Saturn VIII we have introduced incremental improvements to our technology.

- Our Nuclear Engine specific impulse has been increased to 1000 seconds
 - o With the increase in specific impulse, we will investigate the possibility of doing a powered maneuver at Jupiter AND the sun. Our higher specific impulse provides a total of around 23kps dV. We would use about 10kps of this for a sun powered maneuver.
- Our power supply is equivalent is called Advance Space Nuclear (an improved and enlarged version of KRUSTY)- putting out 10 Watts per Kg.

Using a similar layout to the Saturn VIIC we have a first stage mass ratio of 10 so that we could get a total of 23kps from our nuclear engines (13kps to escape earth and do a retrograde maneuver around Jupiter and 10 for a powered maneuver at the sun at 10 solar radii). As for the second stage, we could pick a relatively powerful high-performance engine like VASIMR, but with our 20mt payload we don't have enough mass to have this large of a power plant. The HiPEP engine would seem to fit our needs best- the 40kw model provides only 670mN of thrust but using a ASN type 40kw power plant would only mass 4mt. However, its anemic thrust and low mass flow means that it would take about 800 years to accelerate.

	First Stage	Second Stage	Payload	Totals
M_{structure}	100 (large hydrogen tank; heat shield, NERVA+ engine)	20	40kw power supply (4mt); Engines and Spares (7mt); Xenon tank (3mt);Payload (1mt); Spare Fuel (5mt)	120
M_{Propellant}	2700	180		2859
M_{total}	2800	200		3000
M_{empty}	300 (200+100)	20		
Mass Fraction	3000/300 = 10	200/20=10		

Isp	1000	9600		
dV	23 (rocket- 13 earth/Jupiter, 10 Sun) 80 after powered maneuver	220		300kps

TABLE 8-1 SATURN VIIC TWO STAGE HYBRID WITH A 10KPS POWERED MANEUVER AT SUN

No power plant will operate for 800 years without any maintenance issues. Repairs would need to be made. In addition, if the ASN is like typical reactors the fuel is swapped out every 15 years or so. With even more highly enriched fuel we could perhaps extend this to 25-35 years. Even this will require us to do about 25 fuel swap outs. How much the swap outs would weigh is unknown- but based on KRUSTY numbers of 44kg fuel for 10kW_e, we would need about 200kg of fuel every changeout for a 10kW_e powerplant. With 25 swap outs we would eventually need 5mt of fuel for an 800-year acceleration phase. Furthermore, this is the fuel mass- we will likely need a lot more to keep the replacement fuel packaged, stored and isolated during the voyage.

The same issue applies to the engines. Maintenance or swap out of the thrusters will be required over the centuries. Our total payload and structure mass of 20mt is likely not sufficient to support this kind of operation.

One of our limiting factors with the Saturn VII and VIII is our power supply. We will need to increase our power to kg mass to greater than 10w/kg to get substantial improvement. Furthermore, we are adding a lot of mass by needing to bring dozens of fuel swap outs. There are several ways of mitigating this mass- the simplest is some sort of reprocessing so that the unused ²³⁵U can be recovered and reused. For a small 1mt payload starship this will not be possible. Going forward we will address these two issues.

Despite these issues, and as Chapter 7 demonstrated, leveraging the high thrust Oberth maneuver with the slow but steady electric thruster seems to be a workable combination if scaled up in size where we could repair our equipment and swap out the fuel. Alternatively, if our power supply was increased substantially, and our mass per kW_e were reduced we could accelerate much faster and substantially reduce our acceleration phase.

Cost

Our Saturn VIIIA is very close in design to that of our Saturn VIIA so our costs would be similar. Additional money would need to be spent to design and build a heat shield for our Solar Powered Maneuver. Furthermore, I tweaked up the Nuclear Engine performance by 10% so would add another billion to the development budget. I would place the cost to develop and build this shield at \$3 billion, bringing our total cost to \$42 billion.

With our Saturn VIIIB, we have the substantial challenge of building a high-powered space fission reactor. Instead of needing \$3billion for our Stirling Reactor, I would put a total of \$5billion to build our

space Fission reactor- getting to a fission reactor will require considerably more engineering and development work than a Stirling Reactor. I would place total costs at about \$40billion.

Our Saturn VIIC Two Stage is close in design to our Saturn VIIC with a heat shield. Therefore, I would add \$3billion to this the Saturn VIIC, bringing our costs to about \$44 billion.

Summary and Conclusions

We made a lot of progress with our Saturn VIII. We both maximized our foreseeable technology with Nuclear Engines and introduced an aggressive solar flyby powered maneuver. I don't foresee us improving the nuclear engines much over the 1000 Specific Impulse in the near or medium term. To go substantially above this, we would require engines that used liquid or even gaseous fission engines (see Chapter 17). The NERVA rockets and their kin were all based on keeping the fuel rods solid. To get much higher performance than 1000sec the rocket engines exhaust becomes too hot for any materials to withstand. Eventually we may be able to have liquid or gaseous rockets, but I don't see large nuclear rocket test programs being performed on earth but rather in space which will require us to have a large space-based infrastructure.

Using our proposed 1000 Isp engine with a close 10radii dive to the sun gets us to an impressive 65 kps. I feel confident that building a 1000 second engine and a spacecraft that can dive to within 7 million kilometers of the sun is doable- if challenging. Little is required in the way of new technology. The Parker Solar Probe has demonstrated the ability to approach this close to the sun and survive multiple close passes. If we want to get even closer to the sun- 3 radii or a mere 2.1 million km from its surface, we could reach an even more impressive 85 kps. Shielding the large liquid hydrogen tank from the blistering heat and, if the spacecraft was manned, protect the occupants, are major challenges.

In this chapter we also looked at higher performance electrical thrusters. The limiting issue with these is the amount of power needed combined with their low thrust which means they are not practical for escaping from the sun's gravity and have to run for decades if not centuries to achieve their theoretical velocities.

Our Starship seems to be converging on a two-stage design that has a lot more power available to shorten the acceleration time and reduce the length of time the power is needed. Furthermore, our initial analysis implies the need for extensive maintenance capabilities (fuel changeout, engine changeouts, repairs to components) driven by century and millennium long missions which imply the need for a much larger ship.

Launch Mass Mo (t)	Empty Mass (t)	Mass Fraction	Specific Impulse	Exhaust Velocity (kps)	Final Startship Velocity (kps)	Type of Engine	Power	Dimensions	Mission Duration	Years to go 10LY	Comments

Saturn VIIIA	3,000	150	20.0	1000	9.8	90.0	Nuclear Thermal	Fission			33,333	10radii Solar Powered Manuever
Saturn VIIIA Aggressive	3,000	150	20.0	1000	9.8	120.0	Nuclear Thermal	Fission			25,000	3 Radii Solar Powered Manuever
Saturn VIIIB	3,000	150	20.0	5000	49.1	147.2	Electric Ion-VASMIR	Fission; KRUSTY Equivalent; 200kw			20,387	Theoretical velocity; because of gravity losses will be much less; Engine will operate for 822 years
Saturn VIIIC	3,000	20 NA		5000	49.1	300.0	Nuclear Thermal/ Electric Ion HiPEP	Fission-KRUSTY equivalent; 200kw	41.9m LH Tank; 4.9m Xenon		10,000	Two Stage; powered maneuver around Sun; workable; only 20mt empty final stage; Stage 1- 85kps, Stage 2- 220kps

Chapter 9- Saturn IX- 2070's

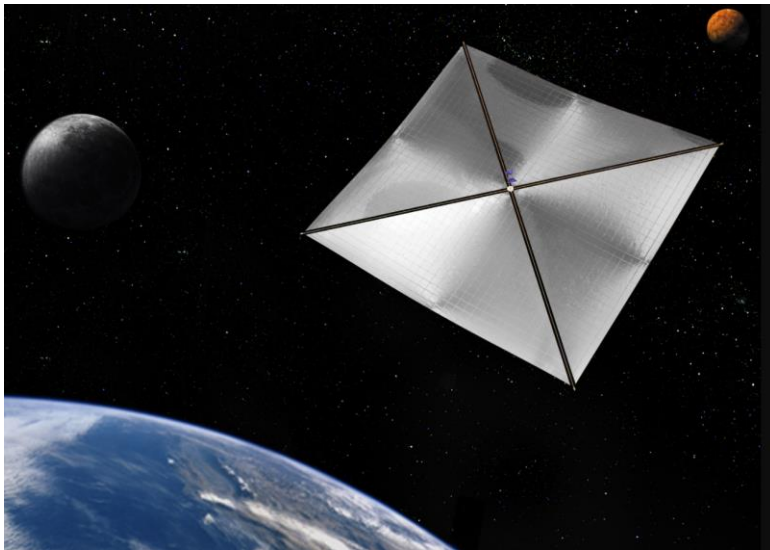


FIGURE 9-1 SATURN IXB (COURTESY OF NASA)

With prior starship iterations, we have achieved sizable speeds with both Nuclear Thermal engines and Electric thrusters. With Nuclear Thermal engines, mediocre Specific Impulse was offset by tremendous gains by using the Oberth maneuver which provided performance gains comparable to the Ion Engine even though the Electrical thruster Engines had a specific impulse five times greater.

Maximizing the Nuclear Engines performance causes us to operate with additional mission complexity and constraints. To perform our maneuver close to the sun we have to kill our orbital velocity (30kps at the earth's orbit) to drop near enough to the sun to get a sizeable velocity boost. The technique we settled on was performing a small, powered maneuver at Jupiter- but this meant we have to do three high thrust engine starts- one to leave the earth or solar orbit where the spacecraft was built, a second maneuver around Jupiter, and finally a large maneuver around the sun. All these add complexity and are likely to take a lot of time- perhaps a decade all told. Nevertheless, for a multi-thousand-year journey, these times are insignificant.

While improvements to the specific impulse of a Nuclear Thermal Engine are feasible, the current design with a solid core will never equal an electric thruster engine. The highest specific impulse reasonably anticipated for a Nuclear Thermal Rocket is on the order of 1000s. There is some hope for more advanced types of Nuclear Rockets including Liquid and Gas Core reactor rockets, which theoretically will be able to achieve specific impulses of 3000s and perhaps as high as 5000s. This kind of performance would be a game changer as they would provide the thrust of a nuclear or chemical rocket but with the specific impulse of an ion engine. Instead of the decades or centuries that electric thruster engines require to get up to speed, nuclear engines could do it in a few days or weeks. Some of these very speculative engines will be considered in a later chapter (Chapter 17) when we will look at more radical technologies and propulsion concepts. The engineering challenges are substantial and there is a lot of uncertainty as to how such a rocket would be built. Furthermore, they would demand a large space-based infrastructure. The engineering research combined with the requirements for a large space based

nuclear industry would dictate that these designs would be more plausible in the late 21st or early 22nd century.

For now, nuclear thermal combined with a powered maneuver need to remain on the table. However, by itself it seems to be inadequate for any voyages less than 25,000 years. The good part about nuclear thermal is that the technology is well developed and all the pieces to build a starship are there- as long as we are OK with a 25,000-year voyage.

In this chapter we will introduce both a refinement and incremental improvements to our Ion engines and our power sources, as well as two other more speculative propulsive engineering technologies that are fundamentally different from what we have considered so far- the Solar Sail and the Mass Driver. Finally we will look at a version of a mass driver for a momentum transfer device.

Saturn IXA- Electric Thruster with beamed power

In the prior chapter, we developed a very fast electric thruster rocket but encountered some issues which have not been fully addressed- primarily the need for vast amounts of low mass power.

One alternative is having an Electric thrust engine whose power is beamed toward it via Laser. In this case we would not need to have a massive MW generator and the problems associated with having its fuel depleted and having its mechanical equipment wear out. This would far more mass available for equipment or permitting a lighter spacecraft with higher performance.

Plasma and Ion engines, while clearly having a much higher exhaust velocity than other types of engines are limited by three items:

- Low thrust
- High power levels
- All fuel must be brought from earth

In Chapter 8, the proposed nuclear power plant we picked was called ASN, that created 10W/Kg. Even with this capability a 1MW powerplant would weigh 100 MT. With our Saturn VII and VIII we looked at a two stage rocket whose final mass was only 20mt- which included a powerplant and some payload- but this was far too small of a payload for a large ASN powerplant.

If we went back to our initial target of 150mt m1 mass, we could have a much larger power plant and our required thrust would also increase. For our 1MW power our generator is 2/3rd of our 150 MT weight limit- and this would provide 25nt of thrust. If we want to boost up our performance even more and get 50 nt of thrust thrusters we would need 2 MW and our power plant would now be 200 MT, exceeding our payload mass.

Beamed power can reduce the problem in item #1,2 and 3. With beamed power, a very large laser beam based in our Solar System, will beam the needed power to the spacecraft. This eliminates the need for a huge powerplant on the starship. With vastly more power available, but minimal power plant weight, we can go with very powerful electric thruster engines and achieve very high performance.

Based on the extrapolating of our electric thrust engines like VASMIR we will come up with a generic engine of the following capabilities:

Isp= 6000

Power= 2MW

Force= 50nt

For mass flow we take our equation

$$F = v_e \dot{m}$$

Where $V_e=6000*9.81=58,860$ mps.

Rearranging:

$$\dot{m} = \frac{F}{v_e} = \frac{50}{58,860} = 8.5 \times 10^{-4} \text{ kg/sec}$$

Our starship final performance is impressive.

$$\Delta V = v_e \ln \frac{m_0}{m_1} = 58,860 \ln 20 = 176.6 \text{ kps}$$

At this ΔV we are looking at a voyage time of just under 17,000 years for a Saturn IXA.

With our reaction mass being 2,850,000kg we will burn through our fuel in:

$$t = \frac{m_{\text{reaction mass}}}{\dot{m}} = \frac{2,850,000}{8.355 \times 10^{-4}} = 3.35 \times 10^9 \text{ seconds}$$

Or about 106 years.

We would still have our issue of needing an initial stage to get our second stage out of the solar system.

Saturn IXB- The Extreme Beamed Version

The advantage of using beamed power is we can imagine tremendous power without having to bring a large reactor. Even though our Saturn IXA performance is impressive, let us continue to increase our power and continue to crank up our performance with a HiPEP type engine. If we used the HiPEP type engine we have a specific Impulse of 10,000sec. Our final velocity would be nearly 300kps. One reason we have not looked at the HiPEP is its tremendously low thrust of 670mn. However, with beamed power we can consider using a lot of thrusters. Suppose we put together 80 thrusters for 54N of thrust. What would our performance be?

Our final specifications would be impressive:

Voyage time to 10 LY: 10,618

Thrust (80 HiPEP): 54 N

Power: 3.2MW

$I_{sp} = 9600$

$\Delta V: 283 \text{ kps}$

To calculate how long the ship will be under thrust we can use our mass flow of the engine along with the total mass of the fuel.

$$\dot{m} = \frac{F}{v_e} = \frac{54}{94176} = 5.734 \times 10^{-4} \text{ kg/sec}$$

calculating how long we will have thrust

$$t = \frac{2850000}{5.734 \times 10^{-4}} = 4.9704 \times 10^9 \text{ seconds} = 157.6 \text{ years}$$

A 3.2MW power plant would weight 320MT (at 10W/kg) or more than our m1 weight. Lets see what it will take to make beamed power work...

Laser Beamed Power- Making this Work

In Chapter 5 we mentioned that the Juno probe to Jupiter has modern solar cells that can put out about 35W/kg of mass. For argument's sake let us assume that we beam laser light that averages twice the intensity of normal sunlight at the earth. In this case our solar panels would generate 70W/kg of power per kg. This is far more than the fission reactors and their 10W/kg.

To generate 3.2MW our panels would weigh 45714kg- or only 45.7mt!

How large would these solar cells be? Let us assume a solar cell can be 24% efficient- the most that is reasonably expected from sunlight and much higher than many of the spacecraft operating now. Assuming we need 3.2 MW of useable power, and assuming the laser light illumination is about 2500 W/m² (about twice that of natural sunlight at the earths orbital distance) with 24% efficiency, we would need a solar panel about 5,333 m² or a square about 73m on a side- or a circular panel about 84m in diameter.

With lasers we may improve our performance even more. Photovoltaic cells that are tuned to the lasers monochromatic frequency of light can achieve in excess of 50% efficiency (Reim, 2022). This can be combined with the increased illumination as long as we design the solar panels to handle the increased photon flux and hence higher heating. With a tailored design it is reasonable that modern, optimized narrowband photovoltaic panels, receiving the appropriate frequency of laser light, may be four times as mass efficient as the solar cells on Juno. This would imply we could get up to 140W/kg. With our power requirement of 3.2MWe this "power source" would mass a little less than 23mt, and with 50% conversion efficiency we could have a solar panel only 2560 m² or a circular panel 57 m across.

Could we build a laser powerful enough and focus tightly enough to provide this amount of power to our spacecraft? This is where the challenge comes in.

How large would our laser aperture need to be to keep this beam tight enough? Light and radio waves are just different frequencies of the same phenomena. Because of this we can use the same equations to determine the dispersal of light as we did with Radio waves and apply the Rayleigh criteria. Using the Raleigh Criterion formula introduced in Chapter 6:

$$\theta = 1.22 \frac{\lambda}{d} \text{ (in radians)}$$

Note from geometry (for small angles):

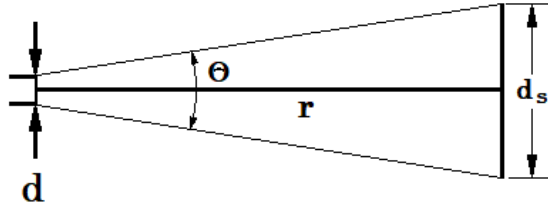
$$\text{EQUATION 9-1 } \sin\theta = \theta = \frac{d_s}{2r}$$

So combining the two:

$$\text{EQUATION 9-2 } \theta = \frac{d_s}{2r} = \frac{1.22\lambda}{d}$$

We can rearrange our equation solving for d to determine the diameter of our laser aperture.

$$\text{EQUATION 9-3 } d = \frac{2.44r\lambda}{d_s}$$



The good part about light is that since its frequency is much higher, its wavelength is much smaller hence our aperture for our laser beam would be much smaller than a similar aperture for a radio beam.

Suppose we wanted our laser beam diameter when it arrives at our spacecraft to be exactly the same diameter as our solar panels- or $d_s = 57m$. Note we can get an idea of r by asking how far will we be when we are done with our acceleration?

When we proposed using the HiPEP thruster we calculated that we would have to provide power for about 158 years. First let us calculate how far our spacecraft would be after 158 years of acceleration. This is actually a bit harder to do since it involves calculus or an iterative process since our spacecraft will not have been accelerating at a consistent rate, but as the starship got lighter, at an ever-increasing rate. If you run the numbers the distance our starship will be at when it gets to the end of its fuel is $3.9 \times 10^{14} m$, or about 2600 AU. Quite a distance, but still only a fraction of that required to travel to the nearest stars.

Let us pick a typical λ for light of 500nm (in the green part of the spectrum).

$$\lambda = 500nm = 5 \times 10^{-7} m$$

$$d_s = 57m$$

$$r = 3.9 \times 10^{14}$$

$$d = \frac{2.44r\lambda}{d_s} = \frac{2.44(3.9 \times 10^{14})(5 \times 10^{-7})}{57} = 8.347 \times 10^6 m = 8347km$$

Wow! If that does not dampen one's spirit, I have a bridge to sell you! We certainly can conceive of a beam that is considerably wider or perhaps operate at a frequency somewhat higher to reduce our aperture, but the reality is that these solutions come with their own issues... either far higher power requirements in the first case, and greater difficulties generating higher frequency lasers in the second.

First Let us assume that our spacecraft intercepts only 10% of the light. Since the spacecraft receives 3.2 MW the laser will need to be 10 greater- or 32MW with a beam diameter of 180m. Using this as our target we would reduce our d to 2643km- an improvement to be sure- but not enough to make this much easier.

The simplest way of reducing this aperture diameter is to accelerate much quicker where the beam does not have to travel so far. But the reality is that beamed power, while offloading most of your starship power mass to a distant location, while solving some issues, raises additional issues that have no simple solutions.

Finally, a word about lasers. Lasers are not 100% efficient in converting electricity to light. Back in the 1970's it was not uncommon that high power lasers to be only 1% efficient but over the intervening decades laser efficiencies have improved so that 25% or even 40% are becoming possible. Nevertheless it is probably safe to assume that lasers efficiencies will never by 100% so for now I would assume 50% is reasonable but that most that can be expected over the next few decades. This means that with your panel intercepting only 10% of your beamed light, and your electric to laser beam conversion at 50%, only 5% of your electric power generation is being used.

We will encounter many of the same issues with beamed power for Solar Sailing...

Saturn IXC- Solar Sailing

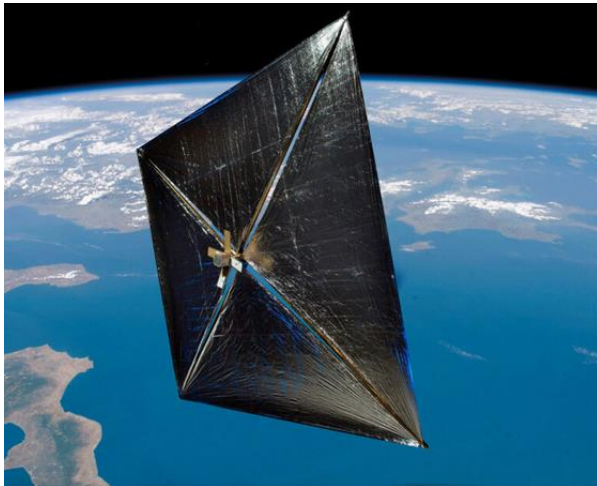


FIGURE 9-3 SOLAR SAIL IN EARTH ORBIT (COURTESY OF NASA)

I admit to being skeptical of solar sailing. There seems to be so many positives that I get suspicious- if Solar Sailing is so great, why has it hardly ever been used?

With beamed power, we eliminated the need to bring along a large power supply. Solar Sailing improves this even further. It has the potential to accelerate ships to very high speeds without any fuel!

Whole books have been written about Solar Sailing. Solar sailing has a lot of variables- some of which are beyond the scope of this book. Solar sailing counts on the fact that photons, the wave particles of light, have momentum. Just like a billiard ball on

a pool table, when the photon hits any surface, it imparts a minute force. How much force does the sun rays provide at the distance of the earth? At the earth's distance of one AU the sun provides about 1366 watts per meter. The pressure exerted on a single meter of area would be:

EQUATION 9-4 $F_{Light} = \frac{I}{c}$

Where c is the speed of light in mps and I is the light intensity per m² or about 1366 W/m².

This is for a black sail, where every photon is absorbed. Note that the physics of this is similar to that if you took a flashlight and turned it on- the so-called photon rocket. In theory the flashlight is receiving a small thrust from the light. We will discuss the photon rocket in Chapter 17. For now, we will use a solar sail which is totally passive in that it does not need power for thrust... the thrust comes exclusively from the photons coming from the sun.

With Solar sailing the situation is a bit better than the above black sail. If we have a perfectly reflective sail, where each photon bounces back, our force imparted on the sail will double, and we would adjust the equation as follows:

EQUATION 9-5 $F_{Sail} = \frac{(1+k)I}{c}$

Where:

k: Sail reflectivity between 0 and 1. A perfectly reflective sail would be 1.

Filling in for c, and setting k=1 we calculate:

F=.0000091 newtons per m²

In reality you could not have a perfectly reflective sail- a reasonably obtainable reflectivity would be 90%. It is likely to be difficult to get higher than this as the solar material is not likely to be flat like a mirror but rather a very thin membrane that will have some wrinkles and will be curved- perhaps in the shape of a parachute.

For a huge, reflective surface under direct sunlight, the force imparted can be sizeable. As an example, let us calculate a flat plate, perpendicular to the rays from the sun with a surface area equal to a disk with the diameter of the earth.

EQUATION 9-6 $A_{Circle} = \pi r^2$

$$A_{Circle} = \pi(6,371,000,000)^2 = 127,516,1177,977,447m^2$$

If we multiply this by our F of .0000091, we get 1,160,396,674 n. This is quite large, but the area of this surface would be astronomical and the mass of the earth even more so! This is the force that in theory impinges on the earth if we assumed the earth was perfectly reflective and flat- which of course we know not to be true. In reality the earth's albedo is about .31 so we would experience less force. Furthermore, the earth is not a flat plate but curved and much of this energy would be directed off to the sides. Regardless this force is insignificant when compared to the mass of the earth which is 5.972×10^{24} kg and that is why the earth does not get pushed away from the sun to a noticeable degree.

In prior iterations of our Starship, we used a m₀ mass of 3000mt, with a final payload size was 150mt. With Solar Sailing, since we are doing away with the fuel our ship becomes correspondingly smaller. For now, let's assume that we are only going on a one-way mission and assume that our spacecraft mass will start (and end) at 150 mt.

A solar sail at the distance of the earth would feel about 5nt of pressure for a 800 x 800 meter square sail. For our first example, how fast would our 150,000 MT spacecraft accelerate? For now, in order to keep it simple, let's assume that gravitational forces are nonexistent, and that the solar radiation pressure does not drop off with distance.

EQUATION 9-7 $F = ma$

Rearranging

$$\text{EQUATION 9-8 } a = \frac{F}{m} = \frac{5}{150,000} = 3.33 \times 10^{-5}$$

If we wanted to get up to the modest speed of 100kps we would take:

$$\text{EQUATION 9-9 } v = at$$

$$\text{EQUATION 9-10 } t = \frac{v}{a}$$

$$t = \frac{100,000}{3.33 \times 10^{-5}} = 3 \times 10^9 = 95 \text{ years}$$

We could of course double the dimensions of our sail to 1.6km by 1.6km which would square our area and force and will now give us 20 newtons of force with a 24-year period of acceleration. Not bad. This assumes the larger sail is no more massive than the original 800 m² one.

However, we have conveniently ignored reality with this example. There are several substantial drawbacks, some obvious and others more subtle.

The first drawback is that we have ignored gravity from the sun, and, if launched from earth orbit, the earth's gravity. If we launched this solar sail from a Lagrangian Point, we could somewhat ignore the earth's gravity but ignoring the sun is not an option- since we are relying on the sun to provide our thrust. If our solar sail were to be released in freefall (i.e., not already being in orbit) our sail would rapidly fall toward the sun at only a slightly slower speed than an object in pure freefall.

When discussing Solar Sails, we need to introduce some concepts. The thrust generated by a solar sail is dependent on the radiation intensity and the size of our sail. Gravity will attempt to pull us down and gravity is a function of the sail/spacecraft mass. A useful concept that will help determine our sails' performance is called sail loading. Sail loading is represented by the formula:

$$\sigma = \frac{m}{A}$$

Where

σ : is the sail loading and usually shown in g/m².

m: is the mass of the spacecraft including the total mass of sail and payload/spacecraft

A: is the reflective Area of the sail

If we have a 100kg (or 100,000 gram) sail/spacecraft combination and our sail is 100m², then our sail loading would be 1000g/m².

A typical material used, mylar, weighs about 7g/m². With our example square solar sail that was 1.6km per side, with an area 2,560,000 m², if we used mylar the sail would weigh 17920 kg. Again, this does not seem to bad!

What would our sail look like? To have a sail 1.6km in size you will need cables as thin as possible carrying the “thrust” back to the ship and depending on the design of the sail, a rigid frame to hold the sail open and to carry the loads back. Below are some configurations that have been considered for Solar Sails.

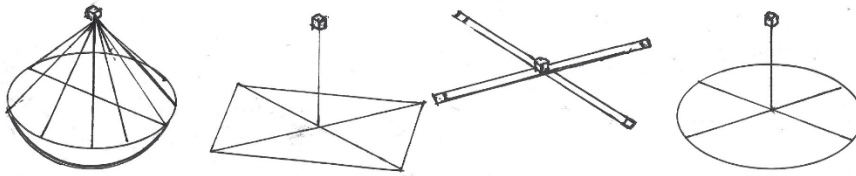


FIGURE 9-4 TYPES OF SOLAR SAILS – PARACHUTE; SQUARE RIGID SAIL; HELIOGYRO; SPINNING DISK

Perhaps our simplest configuration for our Solar Sail spacecraft is the one that looks like a parachute. Simple Geometry would indicate that each of the cables would be a couple of kilometers long. Even a relatively thin steel cable several

kilometers long would have a substantial weight. With all Solar Sails, when discussing multi-ton spacecraft, many challenging issues arise. How would you manage and steer such a large structure? Would it be supported by a rigid structure or in tension like the parachute? There are many different configurations possible, each with its own positives and negatives.

As mentioned previously, sail performance number depends on reflectivity. We will have less than 100% and depending on the material and shape of the sail even 90% may be difficult. If we used a parachute type configuration, where most parts of the sail are not perpendicular to the sun, reflectivity will likely be even less.

Another critical fact- this calculation assumes that radiation pressure at earth’s distance from the sun. In reality, as the solar sail got more and more distant from the sun, the pressure would drop off with the inverse square law- double the distance and we reduce our light force to ¼.

Finally, we have not looked into how the sun’s gravity will affect our sails’ performance. The easiest way is to imagine three cases for a solar sail.

Case 1- Solar Sail Thrust is less than the local gravity

Suppose we had a Solar Sail spacecraft that we placed at zero speed 150 million kilometers from the sun (at the earth’s orbit). If the solar sail provided half the force of gravity, the solar sail would drop toward the sun but at a half the acceleration of a normal object dropped into the sun. The forces provided would look like those shown in Figure 9-5.

In reality the solar sail is already in orbit around the sun. Perhaps it is at a Lagrangian point. If the gravitational force on the solar sail and ship are more than the thrust provided by the photon force on the sail, the solar sail will be pushed, but very gradually and like an ion thruster it will slowly spiral away from the sun. However, ion thruster can maintain the same thrust for as long as there is fuel and power so that eventually their thrust will exceed that of the gravitational force and the spacecraft will escape the solar system. With the solar sail thrust force will reduce as the sail pulls away. This effectively means that while the solar sail will be able to get further and further away from the sun it will never reach escape velocity (if launched on a spiral trajectory) if its thrust is less than the local gravity. It will gradually spiral further away, but its velocity will decrease as it goes into a more distant orbit and the force from the sun diminishes.

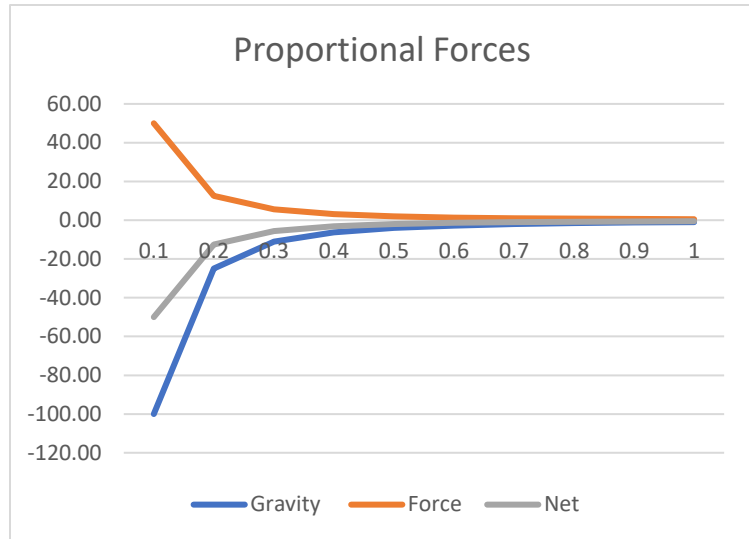


FIGURE 9-5 GRAVITY VS SOLAR SAIL FORCES VS AU FROM SUN

For an actual mission where the photon force will be less than the gravitational force, the sail is likely not to be orientated perpendicular to the sun's rays. In other words, the solar sail will be tilted, and the momentum imparted will be at an angle relative to the incident sunlight. As with a rocket in orbit when it seeks to go into either a higher orbit or to leave the planets/suns gravitational field, it fires its rockets so that its thrust is in the direction it is traveling and not directly away from the object it is leaving. Similarly, the solar sail will likely be tilted at an angle to the direction of the rays so that its thrust is also in the direction it is traveling. Because of this angle, if a flat plane like solar sail was at a 45° angle it will only be getting about 71% of the thrust it would if perpendicular to the sun's rays.

For now, let's assume we do have a flat plane solar sail perpendicular to the sun's rays. What would be our sail loading in order to have the force ½ that of the sun's gravity?

From before we saw that a one-meter flat plate exposed to sunlight at the distance of the earth's orbit would have a force of $F = .0000091$ newtons per m^2 . We have said that our gravity force will be twice this... or $.0000182$ newtons per m^2 or 1.82×10^{-5} . The sun's gravity at the earth's distance is $5.93 \times 10^{-3} mps^2$. Solving for mass:

$$m = \frac{F}{a} = \frac{1.82 \times 10^{-5}}{5.93 \times 10^{-3}} = 3.069 \times 10^{-3} \frac{kg}{m^2} = .003069 \frac{kg}{m^2} = 3.069 \frac{g}{m^2}$$

In this case a sail where the gravitational force is twice that of the photon pressure would mass about 3g/m^2 . This term reflects the combined mass of the spacecraft/sail so in actuality, for any given spacecraft/sail combination (unless we have only a sail and no payload), the sail will have to be lighter than this number.

Let's go back to our first case where we proposed a 1.6km square solar sail with an area of $2,560,000\text{ m}^2$. Our vehicle total mass was 150 MT which works out to about 59 g/m^2 for our sail loading. In Case #1 where we want our photon force to be equal to half our local gravity, our 1.6 square km sail and payload would need to weigh only 7857kg !!!! if we wanted to have a 150mt spacecraft/sail combination we would need to have a sail 19 times

larger- or almost 7km on a side- which would only provide half the force of the local gravity (and assumes 100% reflectivity, that the spacecraft mass is distributed in the sail, and the sail is perpendicular to the sun). Realistically, as mentioned, Mylar, which masses about 7g/m^2 is achievable with current technology- so we would have to develop a material over 50% lighter to achieve a solar sail that generated half the thrust of the local solar gravity.

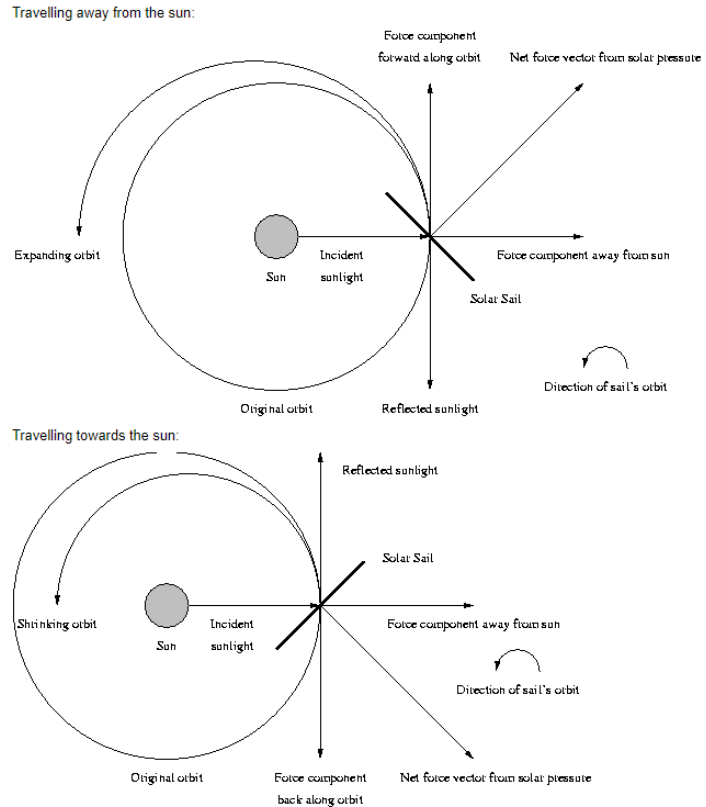


FIGURE 9-6

Case 2 Solar Sail thrust equals local Gravitational Force

In a second case, suppose the photon pressure on the solar sail is exactly equal to the gravitational force of the sun. In our 150mt spacecraft/sail combination to make a Solar Sail equal to the weight we either have to make the sail 38 times bigger (or twice what we showed in Case#1) without increasing our weight or keep it the same size but reduce its weight to $1/38^{\text{th}}$ – not a simple thing to do. For our 150mt spacecraft/sail combination we would need a square sail of about 9.9km on a side.

The interesting thing is that if this Solar Sail were not in motion, it would levitate at a certain distance from the sun with zero velocity. In reality, since this sail would already be orbiting around the sun the moment the solar sail is open it will generate a force exactly balancing the gravitational force so it will head out at a tangent to its orbit at exactly the sails V_{circ} orbital speed and maintain that speed as it exits the solar system. To the sail it would act as if there was no gravity, and it would continue in the direction tangential to its orbit. If the sail were to be constructed at the Lagrangian point of the earth, it would exit the solar system at the speed of the earth orbit- almost 30kps . If such a sail were built at the distance of Mercury and deployed there, it would exit the solar system at the circular velocity of Mercury- or about 48kps .

What is our sail loading of our sail/spacecraft when our gravitational forces are equal to our solar radiation force? Using the values already mentioned in our previous scenario at the earth's distance, Solar radiation is equal to .0000091nt per meter² and the suns acceleration at the earths distance is $5.93 \times 10^{-3} \text{mps}^2$. Solving for m:

$$m = \frac{F}{a} = \frac{9.1 \times 10^{-6}}{5.93 \times 10^{-3}}$$

$$m = 1.53 \times 10^{-3} \text{kg/m}^2 = 1.53 \text{g/m}^2$$

Or, as we would expect, half the mass we used in Case #1. This assumes all of our mass is the solar sail- and no payload is considered. If 50% of our mass was payload our same size Solar Sail would now have to weigh only half the weight or .765 g/m² or about 1/10th of mylar. Furthermore, to achieve this performance the solar sail would need to be 100% reflective- not very realistic. If our reflectivity is 90% our overall sail loading would need to be even less – on the order of 1.38g/m². Again, if 50% of the mass were payload, the sail would need to be only .69 g/m²- a challenging number indeed.

Since a solar sail with this sail loading would depart the solar system at whatever velocity it was traveling when deployed this means that we could put this spacecraft into a highly elliptical orbit around the sun and deploy the sail at its perihelion. In theory, for an object approaching from infinity (i.e., a parabolic trajectory) would reach the escape velocity at whatever the perihelion velocity was when deployed. For instance, if in a parabolic trajectory that approached within one au when it opened its sail at perihelion, then it would exit the solar system at v_{esc} or 42kps.

Suppose our sail were put into an elliptical orbit that mirrored that of the Parker Solar probe, and it opened its sail just at its closest approach (10 Solar Radii- or about 6.9million km). It would then escape the solar system at over 170kps. Before we get too excited, designing a highly reflective material that is 1.53g/m² or lighter, and that can tolerate the high temperatures encountered at a 10 radii solar approach, is extremely challenging and beyond our current capabilities.

Case 3- Solar Sail thrust equals twice the local Gravitational Force

In the third case, the gravitational force is less than the photon radiation force on the sail. For simplicity of our calculations, suppose the photon force on the sail was twice that of gravity. As you can imagine, the solar sail would rapidly accelerate.

Using a sail loading of .765 g/m² our 150,000 kg sail will now have twice the area of our second case. We will now have a sail $1.961 \times 10^8 \text{m}^2$ in area, or for a square sail, 14,000 meters (14km) on a side.

What would our escape velocity be? If starting from V_0 our velocity at v_{∞} with a sail loading of 1.53g/m² we showed in case #2 that our maximum escape velocity from one au would be 42kps. In case 3 we realize that the force on the sail is exactly proportional to the gravitational force, but in the opposite direction. Since we have taken the position that our Solar Sail Thrust is exactly twice that of gravity, solar sail will accelerate exactly at the same speed as an object dropped into the sun's gravitational field from infinity but in the opposite direction.

Expanding on Case #2, if we do some manipulation of the equations, we can come up with the following, where r is a fraction of the earth-sun distance.

EQUATION 9-11 $v_{esc} = \frac{42.1\lambda^{\frac{1}{2}}}{r^{\frac{1}{2}}}$

Where:

EQUATION 9-12 $\lambda = .001574 \frac{\mu}{\sigma}$

μ = Reflectivity

σ = sail loading factor g/m

r = distance from sun in au

Equation 9-11 is a very useful equation. If we plug in a totally reflective sail, $\mu=1$, put a sail at the distance of 1 au ($r=1$) and make the sail weight where the thrust equals local gravity, we have Case #2, where our escape velocity at one au is 42 km/s. Below is a graph showing our escape velocity as a function of how close to the sun's surface the solar sail is started from. This would be the absolute fastest an object could travel and assumes it approaches the sun in a parabolic orbit and deploys fully at its closest approach.

Using this equation, we can calculate what our maximum speeds could be for a particular sail loading being deployed at various distances from the sun. We also can calculate maximum velocities for various sail loadings, as well as plug in more realistic reflectivity numbers. We know that we will not have a perfectly reflective sail, since sails are not rigid and smooth, and hence will not be totally flat and incident to the sun. As before, we will assume that the sail will be 90% reflective or $\mu=.9$. If we assume that manufacturing capabilities exist to make a spacecraft with a sail loading of $\frac{1}{2}$ that of gravity then we have:

$\mu=.9$

$\sigma=.752 \text{ g/m}^2 = .000752 \text{ kg/m}^2$

Then $\lambda= 1.8838$

If we use $r=1$ for the earth distance our Escape Velocity is:

$$v_{esc} = \frac{42.1(1.8838^{\frac{1}{2}})}{1^{\frac{1}{2}}}$$

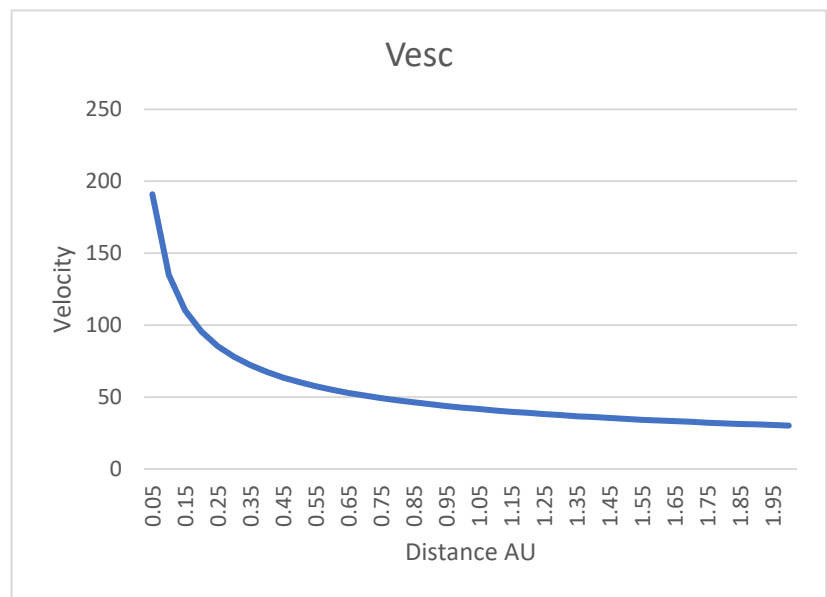


FIGURE 9-7 SOLAR SAIL VELOCITY VS SOLAR DISTANCE FOR SAIL LOADING OF 1.53 g/m^2

$$v_{esc} = 57.783$$

Furthermore, this proportional increase will carry on the closer we can get to the sun.

Plotting this scenario (along with several others) on a graph for a solar sail spacecraft being launched at various distances (and where we assume $\mu=.9$) we can get some very large velocities.

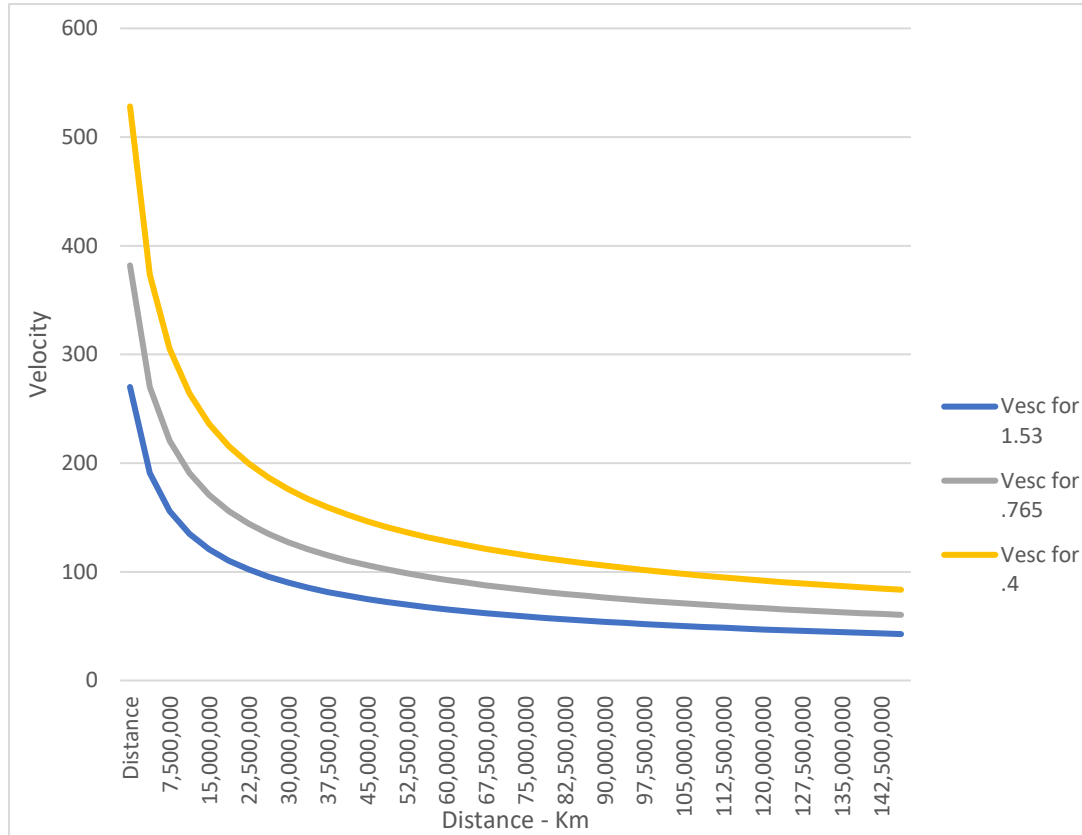


FIGURE 9-8 SOLAR SAIL VELOCITY VS SOLAR DISTANCE (EARTH ORBIT IS AT 150MILLION KM)

A generic version of this equation eliminates the earth distance velocity and suns illumination and makes it applicable to all point light sources:

$$\text{EQUATION 9-13 } v_{\infty} = \sqrt{\frac{\left(\frac{\text{albedo}}{100} + 1\right) L r^2}{2 c d (m_{\text{craft}} + \pi r^2 \rho_A)}}$$

Where

Albedo: reflectivity of the sail in percentage

L: luminosity of the light source

r: radius of sail

c: speed of light

d: minimum distance from light source (in au)

m_{craft} : mass of spacecraft (sail and payload)

ρ_A = Area Density of the sail

Therefore, to get substantial velocities require surmounting two significant and conflicting priorities- getting as close to the sun as possible without melting the sail material (and payload) and making the sail as light as possible but still strong enough not to tear under its loads. I am skeptical that within the next half century or so we will be able to make a light enough solar sail that is many kilometers in diameter and that is going to be able to tolerate the extremely high temperatures it would encounter if launched close to the sun.

Assuming that these two challenges could be met, what would our solar sail propelled spacecraft look like? The simplest may be the Parachute type. Here the sail is kept from collapsing because it spins slowly. This eliminates the need for rigid spars and structure which add only weight without a corresponding increase in area exposed to the sun. With the Parachute type, the sail and cables are always in tension.

For arguments sake let us design two solar sail spacecraft- a very small parachute sail and payload that is only 20kg, and then a large sail spacecraft that is 1000 times larger. For the small sail let's establish a baseline sail, payload combination with the following properties:

10kg sail

1 kg cable supports

9 kg payload

20 kg total weight

Using a total sail loading number of 1.53 g/m^2 if we have a 20 kg sail/cable/payload combined weight this means the sail area exposed to the sun needs to be $13,071 \text{ m}^2$ or 129 m in diameter and a circumference of 405m if a disk or parachute type. Our actual sail material would mass only half this amount or 10kg for an ambitious $.765 \text{ g/m}^2$.

The determining factor on what our escape velocity is will be strictly determined by how close we can get to the sun when we launch. Suppose we approached a very close 3 solar radii. Based on our previous calculations, but assuming a reflectivity of 90%, we can calculate that our sail material would heat up to 1327k. Our v_{esc} would be an impressive 345kps- or the velocity we achieved when we opened our sail.

More realistic would be a 10 solar radii approach. In this case our velocity would be only 189kps- still impressive. Now our temperature would be a much more manageable 727K (still assuming 90% reflectivity).

Suppose we wanted to enlarge our spacecraft by 1000x to have a 20,000 kg spacecraft. Using the above ratio's we should have:

10,000 kg sail

1000 kg cable

9000 kg payload

20,000 kg total weight

In this scenario, the sail is 10,000 kg but it is also much larger- about 4.1km in diameter with a circumference of 12.8km. The number of cables would have increased by the amount our circumference has increased or by 31.42x but now they also need to be about 31x longer to keep our sail proportions the same- so the cable mass would grow (as expected) also by 1000x or to 1000kg .

There has been talk about building space elevators out of carbon nanotubes and other such high-tech inventions. The holy grail of space elevators is one that reaches down to the surface of the earth and can carry payloads up to

geosynchronous orbit. If these items come to pass, and the materials are able to withstand the rigors of space, then the weight of the cables may be so light as to not be important. The same materials would like be applicable for solar sails. If the sail material itself were made of super strong carbon sheets they would allow for very small sail loading number. It seems possible that solar sails would become practical when space elevators become technologically possible- many of the challenges are similar.

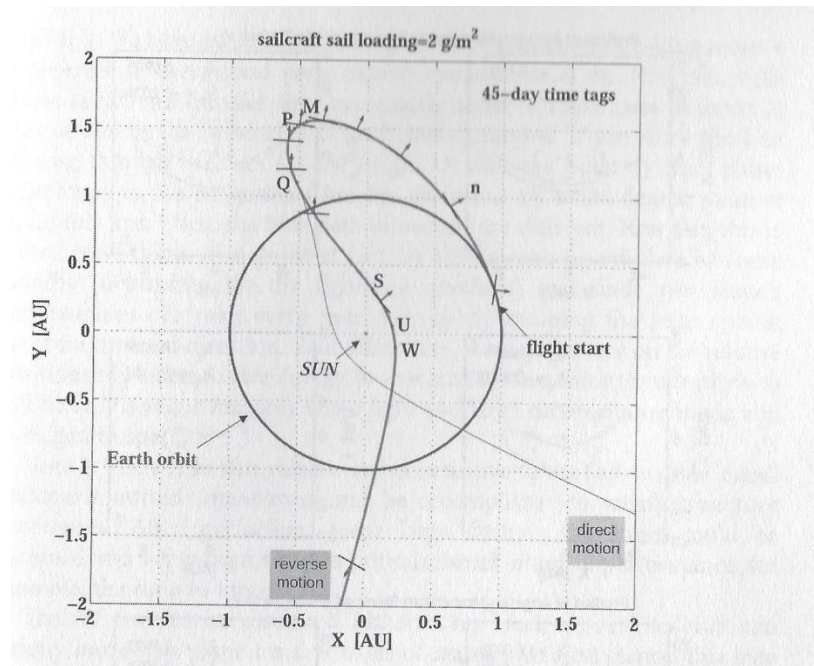


FIGURE 9-9 APPROACHING THE SUN WITH A SOLAR SAIL (GIOVANNI VULPETTI, 2008)

To maximize final velocities, it is highly desirable to get the solar sail as close to the sun as possible.

As we saw with the powered maneuver, dropping an object close to the sun is quite difficult since you must negate the orbital velocity. However Solar sails can be used to lower a spacecraft closer to the sun since their thrust direction can be varied by tilting the sail as was shown in the Figure 9-8. (Giovanni Vulpetti, 2008). These techniques can be used for all sail loadings so that in all our three cases, speeds can be greater than if launched on a spiral trajectory.

Opening up a large solar sail, especially near the sun, has many challenges including how will the sail be packed? How will it handle the uneven loads as it unfurls? Small solar sails, on the order of 10 or 20 kg, will be much easier. By keeping the sail relatively small we minimize the engineering complexity of building and deploying huge sails as well as simplify our manufacturing challenges. If used near the sun, even though they would experience a relatively high acceleration, their relatively small weight should make the opening up operation much easier. For this reason, I believe small solar sails may play an important role and I will consider them several times in this book. We will also look at the beaming light to solar sail to permit the acceleration phase to continue much longer- similar to what we proposed in the Saturn VIII B where we beamed power to onboard Solar Panels.

For large solar sails and multi-ton spacecraft I am skeptical of Solar Sailing in the short and medium term. Much like the space elevator, I think the technical complexities and engineering challenges should not be underestimated. Over the next thirty or so years, as manufacturing techniques improve and the space industry expands, I believe we will come up with sail loading numbers that are down to below 1 g/m², which should be sufficient to keep the sail, cable, and payload under the magical target of 1.53 g/m² for the whole vessel. However, I am more skeptical that they would be able to tolerate a very close approach to the sun, or the ability in the 21st century to build sails dozens of kilometers across. If propelled using beamed power I am skeptical of our ability to generate a beam of many Gigawatts of power.

Regardless of my concerns, the advantages of Solar Sailing are too substantial to be ignored, even if the technology is likely decades away from being available. Before we move on, let us look at using beamed power to accelerate our sail.

Laser Beamed Thrust for Solar Sails

Beamed power provided an alternative to the need to have large nuclear reactors on our Starship. This allows for the use of lightweight photovoltaic cells instead of heavy reactors and eliminates the problem of not having any sunlight in deep space. A laser beam can be kept coherent for a long distance. What if we extrapolate the beamed power solution we proposed for the Saturn IXA and instead of just providing power through solar panels, we use the laser to propel a solar sail spacecraft? In theory this would be a perfectly acceptable solution that would eliminate the need for all fuel. Furthermore, our solar sail is vastly larger than our solar panels so that our beam would not necessarily need to be as tight.

The laser power required to push the solar sail is many times more than what we required for the Saturn IXB. By building such a large laser, we are essentially building a huge photon rocket, and beaming that momentum to a sail with the added disadvantage that our laser beam will spread out considerably across the AUs of space so only a small fraction will fall on our sail. As with our beamed power option, beam dispersion and the inefficiencies of power generation and the conversion to laser power, we may very well need to generate 10 or 20 times more power than actually is transferred to the sail.

Solar Sails need a lot of photons. Assume we want to keep the same power we beamed for our beamed solar power- or twice the 1366 watts per meter of the sun for our target 24 years. For a 150,000kg spacecraft, with a sail loading number of .756 we had calculated that the surface area of the sail would be 300,000,000 m² or 19.5km in diameter. The power falling on this area would be:

$$P = \frac{w}{m^2} (A)$$

$$P = 2500 (300,000,000) = 750GW$$

As with the Saturn IXB lets assume an efficient laser operates at about 50 and assuming aggressively that the sail intercepts about 1/10th of the beamed power we can optimistically assume only 5% of the power generated will actually be available to propel the sail. Therefore, we would need about 15TW of power. The laser beam, since it does spread over distance will imping more power at the beginning of the voyage than at the end, but we will assume 2500w/m² is the average.

That's a lot of power. The Raleigh criteria requires the laser aperture be very large. Somewhat offsetting this is the fact that our solar sail is a much larger target than the solar panels... in this case about 20km in

diameter. If you increase your aperture as the sail goes further you will tighten your beam and be able to keep the light intensity consistent, giving you consistent acceleration. This calculation does not take into account the fact of how hot our sail can get? When we calculated our power requirement, we just assumed a radiation intensity was twice that as experienced from an earth orbit. In reality, the intensity of the beam would be restricted to whatever your sail material can handle. Furthermore, we have also ignored the fact that a heated sail (i.e. not totally reflective) will emit photons out the back and reduce our thrust. A more complete equation for acceleration would be:

$$\text{EQUATION 9-14 } a = \frac{\varepsilon\mu}{\alpha\sigma} \left(\frac{\sigma_{SB} T^4}{c} \right)$$

Where

a = acceleration in m/s^2

ε = emissivity

μ = sail reflectivity

α = absorption coefficient

σ = sail loading

σ_{SB} = Stephan Boltzmann radiation constant ($5.67 \times 10^{-8} \frac{W}{m^2} / K^{-4}$)

T = Sail Temperature in Kelvin

c = speed of light ($3 \times 10^8 mps$)

The power required would be:

$$\text{EQUATION 9-15 } P_s(W) = \frac{mca}{2\mu}$$

To calculate the diameter of the sail (d_s) we can use the equation:

$$\text{EQUATION 9-16 } d_s = 2 \left(\frac{A_s}{\pi} \right)^{\frac{1}{2}} = 2 \left(\frac{m}{\pi\sigma} \right)^{\frac{1}{2}}$$

Where:

A_s = Area of the sail

As an example suppose our sail material can stand a temperature of 400 K. A typical $\varepsilon = .05$, $\alpha = .15$, $\mu = .9$ and $\sigma = .756$. Our mass is as before 150,000kg.

$$a = \frac{.05(.9)}{.15(.756)} \left(\frac{(5.67 \times 10^{-8})^4}{3 \times 10^8} \right) = .00768 m/s^2$$

How much power would be needed?

$$P_s = \frac{150000(3 \times 10^8).00768}{2(.9)} = 1.92 \times 10^{11} = 192GW$$

As before, this is the power being delivered to the sail. If we assumed that only 5% of the power generated actually makes it to the sail, we would need 3.84TW.

Finally, this sail would be accelerated at $.00768\text{m/s}^2$ assuming the laser aperture is increased as our voyage progresses so that the incident light level is kept constant. Assuming we want to accelerate to 300kps how long would it take? It turns out that we would require 455 days to accelerate to this speed.

Keep in mind that besides the tremendous power involved, and the tremendous aperture of the laser we would still have to build a very lightweight sail- in this case assuming that the sail masses 50% of the total mass of 150mt, then we will have a sail that weights only $.000378\text{kg/m}^2$ and will have an area of 397million m^2 - or a circular sail 22kilometers in diameter.

When we consider solar sailing, I feel confident that this technology will play a role in the future. The advantages are substantial- no fuel and effectively a very high escape velocity. However, the primary weaknesses with the Solar Sail (as with the Photon rocket) is the extremely low momentum of photons- we don't build rockets with high power laser beams propelling them because the amount of light and therefore power needed are literally astronomical. The advantage of a solar sail is that the light is provided by the sun and is free. In addition, as opposed to the photon rocket, the momentum of each photon would be about twice that of a photon rocket since the sail is reflective. However, you still require a tremendous number of photons to get a sizeable thrust and therefore acceleration, which requires us to have a huge reflective sail but light said and to either get very near to the sun or to build extremely large and powerful lasers.

Saturn IXD- Mass Driver

Are there additional propulsion options that provide the high Isp of the electric thruster but with higher thrust levels? There are not many but there are a few. One we can consider is the Mass Driver. Mass Drivers can, if sufficiently large, achieve the high Isp of an electric thruster but with several thousand times the thrust. Mass drivers have never been used in space, but small models have been built on earth. A related technology are rail guns, currently being researched for use by the military.

A mass driver is totally different than a chemical or nuclear thermal engine which counts on thermal energy to accelerate a mass- it more closely resembles the Electrical Thrusters and Ion engines which count on magnetic field to accelerate ions. A mass driver does not accelerate ionized atoms for thrust but rather it accelerates a magnetic bucket containing any material available as a reaction mass. A mass driver is related to a linear motor in that a traveling magnetic wave pulls along a magnetized bucket at ever increasing speeds until it is ejected at the end of the mass driver. The magnetic field both pulls the

bucket from the front and pushes from the rear. In most versions the bucket can be decelerated and reused but this could significantly lengthen our mass driver and add additional complexity. A more simplified solution would be to throw the bucket away. The primary difference between the mass driver and a typical electrical motor is that a motor has mechanical brushes that provide the power to the armature so it can generate a magnetic field. At the speeds the mass driver will be accelerating its magnetic bucket, any physical contact like a brush would be vaporized. For this reason, the mass driver

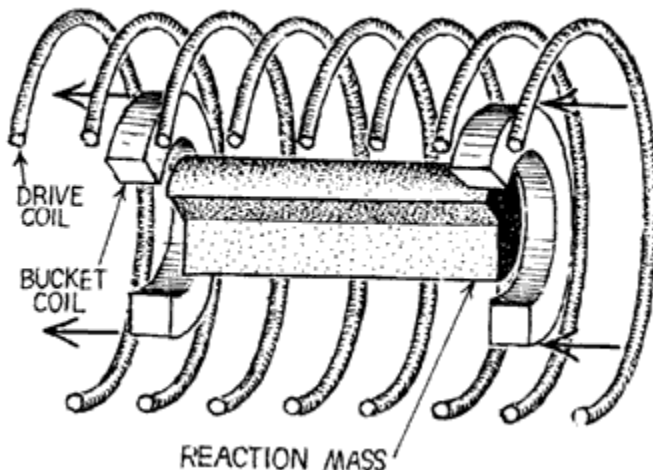


FIGURE 9-10 MASS DRIVER BUCKET AND REACTION MASS (KOLM, L5 NEWS: MASS DRIVER UPDATE, 1980)

would have a self-levitating bucket with payload that would not come in contact with any physical components. The lead coil is pulling or attracting the payload/bucket and has a centering effect while the pushing back end has a destabilizing effect. By making the “attractive pulse a larger amplitude than the repulsive pulse, then the net effect will be stabilization of lateral motion”. (Arnold, et al., 1979). Whether the bucket is actively magnetized through some sort of current from a small battery or storage device or is made of a superconducting material which retains its magnetism imparted before launch, or through temporarily retained magnetism

in the case of some metals, like aluminum, would need considerable engineering design work before the best solution is identified. However, the proposed acceleration rate of 10000g is greater than that which was considered in 1977 Summer Study and subsequent updates which usually selected an acceleration of 1000g (Arnold, et al., 1979).

The mass driver provides multiple advantages over the Electric Thrusters/ ion engine-

- Much larger thrust
- It can use anything for a “mass”. This means you do not have to “import” your fuel or your mass from the earth. You can put a mass driver on a small asteroid and use the asteroid soil as your mass. However with this proposed configuration, a sizeable portion of the mass will be the bucket will be some sort of conducting or superconducting metal.
- They should be relatively efficient in converting electrical power to momentum.

Unfortunately, since they are related to electric thrusters, mass drivers do not help much is with power usage. Even though they are more efficient than electric thrusters, the fact that their propulsive force is much higher mean that they will use a lot of power.

In addition, every possible solution we consider invariably seems to bring along new problems. Mass drivers have the following disadvantages:

- There is a lot less manufacturing and design experience with large mass drivers compared to an Ion or Electrical thruster. While small scale and theoretical studies indicate they will be very

doable, the fact is that the mass drivers we will be considering will be many orders of magnitude larger than anything built to date- they will require more development to make viable.

- Mass drivers quickly become very large and hence very heavy as opposed to the fairly light and small Electrical Thrusters we have considered.

Let's do a preliminary design with the following requirements:

$m = 1\text{kg}$ mass

$a = 100g$ acceleration (or 981 mps^2)

$s = 100$ meters long

What would be the "exhaust velocity"?

EQUATION 9-17 $s = \frac{1}{2}at^2$

Rearranging the terms:

EQUATION 9-18 $t = \sqrt{\frac{2s}{a}}$

$$t = \sqrt{\frac{2 * 100}{981}} = .45 \text{ sec}$$

With this as our time that our mass is accelerating, we plug into:

$$v = at$$

$$v = 981(.45) = 443$$

Or an Specific Impulse of 45 seconds

This is well below that of even a Chemical rocket. Suppose we bump up the acceleration to $1000g$ and the length of the mass driver to 1km ? By making the acceleration ten time faster but our length $10x$ more the actual amount of time spent accelerating ($.45\text{sec}$) would be the same and therefore the final speed is simply related to the acceleration- or in this case $10x$.

$$v = 9810(.45) = 4430\text{mps or } 452 \text{ seconds}$$

We can see that we can increase our specific impulse by increasing the acceleration and/or increasing the driver's length but to get truly large exhaust velocities will require a very high acceleration and a very long mass driver. To come close to that of the performance of Electric Thrusters how long would our driver need to be?

Suppose we want to have a specific impulse of 5000 sec (or $50,000\text{mps}$) to equal that of a modern Electric thruster? Assume we can keep the $1000g$ acceleration. To get to the 5000 sec speed our exhaust velocity will be about $50,000\text{ m}^2$. Our length can be calculated as follows:

$$t = v/a = 50,000/10,000 = 5 \text{ sec}$$

$$S = \frac{1}{2} (10,000) 5^2 = 125,000 \text{ m} = 125 \text{ km}$$

That's a long engine!

I initially selected a 1000g acceleration because it seems reasonable and doable. Mass Driver 2, a test of the mass driver principle was a demonstration model being built in the late 1970's. It consisted of a 4" caliber tube and was designed to accelerate a mass at 500g (Kolm, L5 News: Mass Driver Update, 1980). This mass driver was apparently never completed but its design capabilities were several orders of magnitude greater than the first mass driver built- the creatively titled Mass Driver 1 which was capable of accelerating a payload at only 33g (Henson, 1977). Even though I never could establish as to whether it was built, the published literature seemed to be very optimistic that the 500g performance could be obtained, despite the fact that the device was purely a low budget affair.

These sorts of accelerations are on the low end of what is typical for many guns. It is also on the low end of what the Navy is considering for their ship mounted railguns. I tend to believe that in the vacuum of space, and with the expenditure of research and development dollars, along with the fact that the payload being launched would be comparatively small- from 1 to 20 kg, whereas army and navy shells can easily be 10x or 20x heavier- much higher numbers would be possible.

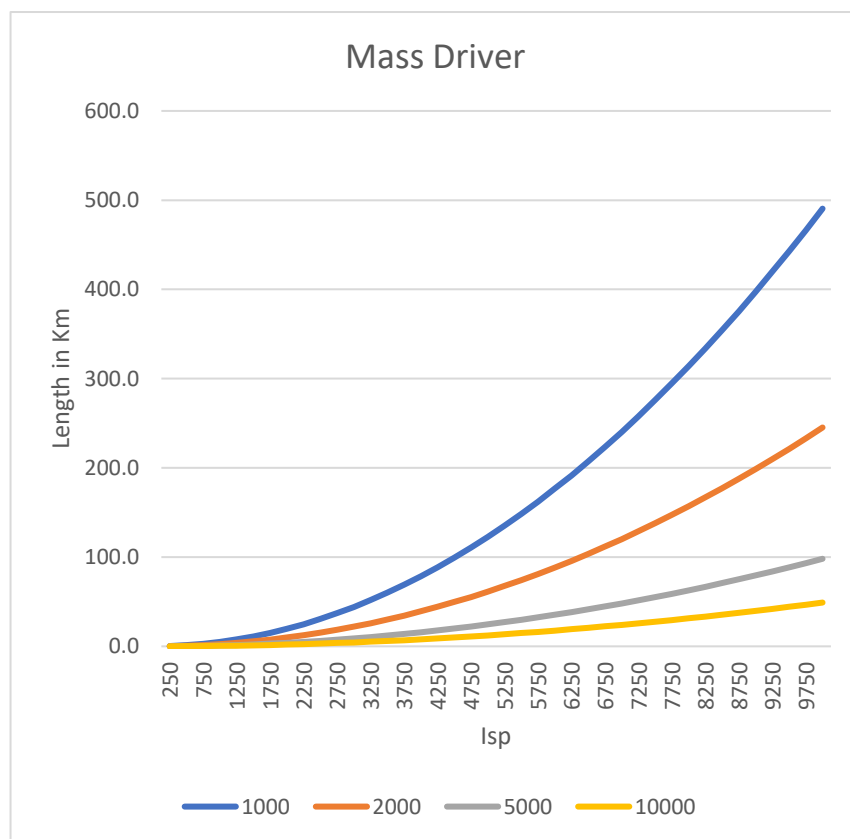


FIGURE 9-11 MASS DRIVER LENGTH VS ISP FOR VARIOUS ACCELERATIONS

Electronics have advanced considerably since the 1970's when Mass Driver 1 and 2 were designed. Modern electronics would monitor the progress of the bucket and rapidly adjust the currents in the coils to control the bucket acceleration. As opposed to the small experimental accelerators built in the 1970's, a modern engineered Mass Driver should be able to generate far more powerful magnetic fields, more accurately measure the speed and more rapidly adjust the required current flows and hence magnetic fields. To get an idea of how large some of these mass drivers can be, in Fig 9-11 I plotted the required lengths for different Isp for

various g accelerations. As can be seen, higher accelerations are required to keep the mass driver lengths reasonable. For this reason, I believe we will need to achieve higher acceleration than 1000g. If we extrapolate to 5,000 g and pick a target Isp at 5000sec the engine would be 1/5 the length and the acceleration would take 1/5th the time or 1 full second.

How much would a mass driver weigh? Since no large mass drivers have ever been built or designed this is a hard question to answer. A mass driver would have to have large, closely spaced coils, be able to carry large electric currents, be rigid enough not to flex excessively, and strong enough to withstand the thousands of g's acceleration of its "mass". If we could build a mass driver that has a weight equivalent of 1000kg per linear meter this would equate to a total mass per kilometer of 1000MT and our 25km version, we would weigh in at a sizeable 25,000 MT- or almost 8x heavier than our fully fueled Saturn. What would be the performance of a more reasonably sized mass driver if we assigned about 1/3 of our starship mass to the propulsion system. Based on our 150MT starship would dedicate 50 MT to our propulsion system. This would get us a mass driver of 50 meters- clearly too small for our needs.

As we have seen, as opposed to rockets and ion engines that are fairly light and compact affairs, Mass Drivers are not!

The wiring carrying the large electric loads and resulting high magnetic fields may be made of superconducting materials and therefore may need some sort of active cooling but here we may luck out... since this engine is to be used in deep space where the temperature is only 3.7 degrees above zero, we may be able to operate without this extra mass of an actively cooled system by using high temperature superconductors.

Perhaps we have been overly pessimistic in our mass driver weight assumptions- how reasonable is our assumption of 1000kg per meter? Can we lower this and if so by how much? Since I could not find much literature on this, I had to make some assumptions. In North Dakota is one of the tallest structures in the world-the KVLV-TV tower- at 1,950-foot (594m) tower topped by a 113ft antenna for a total height 2063 ft tall. The 1950 ft structure weighs 864,500 pounds (392,131kg) (Valleynewslive, 2010). This works out to 660kg per meter. This probably would be a good starting point for calculating our mass driver weight. We would have to add some mass for the actual mass driver drive coils and wiring, however the radio tower in ND has to endure high winds and at the bottom is supporting over 390mt whereas our mass driver would likely not see more than 10mt (assuming 1kg accelerated at an aggressive 10,000g). Therefore, my initial feeling is that our first cut at a weight of 1000kg per meter may be overly cautious and can be reduced somewhat. In the Space Settlement Survey, the track was aluminum and they projected a weight of only 27kg/m (Johnson & Holbrow, 1977, p. 128). This mass driver was located on the moon and this mass did not include the support piers that were positioned every 10m, nor did not include any power and stiffening/tensioning cables. Oscillations and flexing of our mass driver will be a problem and we will need considerable stiffening to minimize this flexing which will add weight. Given the small projectile size I could see the mass of our mass driver being only 500kg/m but this may prove to be excessively optimistic.



FIGURE 9-12 KVLV TV TOWER NORTH DAKOTA

If we were launching 1 kg projectiles the actual dimension of the barrel would be quite small. For an object with the density of a steel ball it would be on the order of 6cm in diameter. We have not looked at what material we will be projecting down the accelerator, so the exact dimension is unknown. If the material is regolith or some sort of asteroid material it will be considerably less dense than steel, iron or nickel. Even the least dense material that might be considered, water ice, would be a sphere only be about 12cm in diameter. We must also keep it mind that the bucket may make up a majority of the mass and the bucket will have to be some sort of actively charged coil or passive superconducting metal. The shape of the projectile would likely be cylindrical- with a relatively small diameter bucket plate up front and in the rear with the rest of the mass in a cylinder along its axis as in Figure 9-10. This bucket and mass would levitate inside the barrel. The barrel would be surrounded by conducting coils that were rigidly mounted to our structure so as not to flex when accelerating the projectile. What the bucket is made of is unknown and would require engineering studies to determine the optimum material.

In the sketch I have selected a design similar to that of a radio tower. The center section is the barrel down which our projectile passes. The central barrel is likely to be only about 10cm in diameter. The outer, shaded section is our magnetic coils and associated wiring. This is stiffened by the frame- three corner braces linked with steel or aluminum that will resist flex. The center shaft are connected to the frame by tension wires. Whether our 1kg projectile accelerates at 5000g's or 10000g's, this force will likely not be much of an issue for the mass driver structure- it is far less than what the stress the lower part of the radio tower had to support.

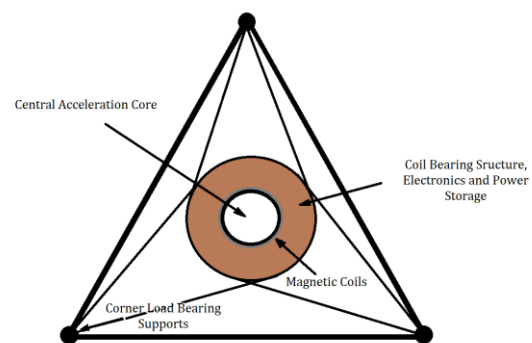


FIGURE 9-13 MASS DRIVER CROSS SECTION (NOT TO SCALE)

With the Mass Driver we have both positives and negatives compared to an Electric Thruster:

Positives

- More efficient from a power perspective. It appears that at least one analysis indicated a mass driver could be 80% efficient at converting electrical power to propulsive force (Kolm, L5 News: Mass Driver Update, 1980). While some electric thrusters can approach this, most seem to be in the 40-60% range.
- Can use anything as a reaction mass (though the bucket is another story). The practical effects are that storage of reaction mass is much easier- no need to handle liquids or gases.
- Greater thrust and mass flow. Typical mass drivers generate many times the thrust of an Electric Thruster.

Negatives

- Weight. The Mass Driver is far heavier than Electric thrusters to get an equivalent specific impulse.
- Complexity of design. Technically mass drivers are simple devices but to optimize, keep mass as low as possible and specific impulse as high as possible will require considerable design work.

The design of the bucket may not be easy and the need to mass produce these buckets, as well as building a multi-km long mass driver will be challenging.

My reluctant conclusion is that the relatively small mass driver suitable to be carried for our Saturn IXC will have a performance worse than even our chemical rockets. While the mass driver has the ability to have very high specific impulse the lengths that this would require a structure mass far more than our budget of 150mt would allow. This situation may change if our starship becomes far larger and we can budget more mass for propulsion. Other improvements could be to lighten the mass of each meter or further increase the acceleration thereby reducing the length required. The fact is that even though the mass driver is far too heavy in this application, its much greater thrust makes it attractive if we have a larger starship or are content with a very low specific impulse. Furthermore, the fact that much of the reaction mass is low value dirt, or metal, vs expensive and rare Xenon or Argon means we will keep the mass driver in the back of our minds, but for now we will give up on pursuing the mass driver for our Starship.

Pellet Propelled

Before we move past our mass driver discussion, I would like to discuss a variation of this idea. As with Solar Sailing, it does not appear that the Mass Driver would be appropriate for our vessel due to its excessive mass to get to a worthwhile specific impulse. However, a variation on this concept was introduced in 1979 by Clifford E Singer of Princeton University (Singer, 1979). His idea was to build a large mass driver within the Solar System that launched a stream of pellets that impact in some manner on the starship thereby imparting their momentum. Several variations were proposed on how their momentum could be transferred. The pellets could be stopped and then repelled via a powerful magnetic field on the Starship, thereby imparting both their arrival momentum as well as their reflected momentum- similar to a reflective solar sail and photons. Alternatively, and more simply, the pellets could impact a plate where they would just vaporize into plasma. Others have even proposed that the small pellet hit at such speed that if the ship dropped its own small pellet that impacted the incoming pellet, the two pellets would collide at such a speed as to initiate a nuclear fusion reaction boosting considerably the thrust provided. In this case the initial analysis indicated that the pellets would have to hit at some 200kps.

In Singers design the following was proposed:

- A mission similar to the Daedalus flight 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. Furthermore the targeting has to be so accurate that the pellets would have to hit the ships impact plate.

- The tremendous speed of pellets leads to the requirements for a massive pellet launcher
- The tremendous speed of the pellets also required a tremendous power supply
- The tremendous speed of the pellets required huge accelerations. 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. Our starship will carry no fuel (unless it needs to slow down at the target star). This means our nominal 3,000 mt starship will only be 150mt- the payload only. Not having to waste most of your mass and therefore energy accelerating your dead fuel mass reduced 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, less than 5% of the power generated would go to propelling a spaceship.

Despite these benefits the scheme proposed by Singer is too ambitious for our 21st century engineering and manufacturing. A 10,000 km launcher, correcting stations every 340 AU, and 15GW power supplies are too challenging. However, if we reduce our mission requirements, in particular the .12c starship speed requirement to a much lower speed, can we adapt this idea for a 21st century starship? Using conservative technology, could we rethink the pellet idea?

Let's assume the following:

- Our starship weight is 150 MT
- Our pellets are 10 grams
- Our pellets will be impinging on the Starship impact absorption plate at 10kps. The nature of this plate is To Be Determined (that is the engineer's way of saying I don't know).
- We will assume an inelastic collision and assume 100% efficiency of momentum transfer
- We will have a target velocity for our Starship of 300kps
- We assume that one pellet per second impacts the ship absorption plate

From the ship's point of view, 10 grams impinging per second at 10kps imparts a momentum of 100 kg m/s. Our 150mt spacecraft will feel an acceleration of $100/150,000$ mps or $1/1,500$ mps². To get to a 1 mps gain in speed we will need 1,500 seconds or 25 min.

Our final ship speed will be 300kps or 300,000 mps so we have to multiply our 1500 seconds by 300,000- or 450 million seconds- about 14.3 years.

This is a long time but considering or 300 kps our spacecraft will take 10,000 years to go 10 LY, this is not excessive. Note that at the end of the outbound acceleration part of our voyage, when the Starship will be traveling at nearly 300kps, the pellets will be arriving at 10 kps but will be moving relative to the launcher at 310kps. The pellets themselves are 10 kilometers apart. This implies that near the end of our voyage the launcher will have had to fire one pellet every $1/30^{\text{th}}$ of a second- or 30 pellets per second.

Of course, when the Starship begins its voyage and is traveling at about the same speed as our launcher the launcher will be only sending out a pellet a second. Over the course of the mission that rate of firing will gradually need to be increased to 30 per second.

Note also that the total mass launched that would impinge on the ship at 10 grams per second would equate to 4,500,000 kg- or 4500 MT. The amount total amount of pellets fired would be 450 million.

The biggest engineering challenges would be the mass driver, its power supply and the need for extremely precise velocity and targeting. Singer assumed incredible accelerations combined with a tremendously long launcher. Our 300 kps target is only about ½ of 1% of Singers pellet speed of .25c. Singers ten-gram pellet is very small and as such an acceleration of 1000 or even 10,000g is likely doable... though I struggle to figure out the design of the superconducting solenoid. For arguments sake let us assume that we can do a 10,000 g acceleration.

$$a = 100,000 \text{ mps}^2$$

$$v = 310,000 \text{ mps}$$

$$t = 3.1 \text{ sec}$$

$$s = \frac{1}{2} (100,000 \cdot (3.1)^2) = 480,000 \text{m or } 480 \text{km}$$

This is quite long and massive- however it is much more practical than that proposed one by Singer.

How massive would this launcher be? Based on our quick back of the envelope calculations from earlier in this chapter we stated that the launcher weighs 500kg per meter. The pellets are so small in this configuration that this is likely doable. It would weigh 240 million kg or 240,000 mt. This is likely on the small end for required mass as for redundancy and the shear rate of pellets being I foresee a gatling gun type of arrangement, perhaps with as many as 6 or 12 mass drivers. This would drive our mass up again to perhaps a million mt. For space structures, this million metric ton device is truly “astronomical” but as mentioned before, some ocean vessels on earth weigh 500,000 mt. A large skyscraper or dam would weigh even more. Most of the mass of our driver would likely be iron or aluminum and would be mined from an astronomical body.

As challenging as the mass driver launcher would be the large power supply needed to energize the launcher is even more challenging. At its peak, toward the end of its mission, it will be launching thirty pellets of 10 grams each per second- or .3kg per second at velocities of 310kps. Using our energy equation toward the end of the acceleration part of the mission we would need:

$$\frac{1}{2} (.3)(310,000)^2 = 1.4415 \times 10^{10} \text{ joules per second. With conversion inefficiencies we would need about } 18 \times 10^{10} \text{ joules. That is a lot of power but is doable.}$$

An equally challenging aspect would be keeping the pellet stream on track. I do not foresee station correcting stations spread out over tens of billions of kilometers a very reasonable solution, at least in this century. There are some possible ways around these pointing issues which we will look at in later chapters.

I feel that the baseline Pellet proposal as proposed has merit but like the Solar Sail, not ready for prime time. Perhaps in a century or two we will have the ability to build such devices and associated support equipment. Part of the challenge with the mission as proposed by Singer is that he wanted to keep the

mission down to 50 years. If the velocity of the Starship is decreased substantially (hence making a much slower moving rocket) the pellet proposal may become feasible.

Technology- Power Supply- Fission

Power alternatives are limited to some sort of fission reactor since, without radical engineering improvements that would permit large, compact fusion powerplants, we are stuck with the fission power plants already discussed. Some incremental improvements could be made that permit higher power output per kg of mass, but these are not likely to lead to the order of magnitude improvements. In Chapter 8 we used a near-midterm capability (over the next few decades) of a nuclear reactor that generates 10W/kg of power. Based on reactors from earth (including those used on aircraft carriers) a 25-year life can be anticipated. The Seawolf submarine is designed to have its reactor last for 33 years (Ragheb, 2021) so depending on the design somewhat longer periods may be possible. I speculated in an earlier Chapter about a very high power and light power supply that produces 20W/kg which I believe is technically possible and will be using starting with Chapter 10.

What kinds of fission power plants are available and how do we make them last for thousands of years? Why do we need to change out the fuel supply on a fission power plant every few years and on a military ship every 25 years?

We have improved our mass/power efficiency to 20W/kg but have not addressed our fuel changeout requirements. One long-term solution I can think of is that spare enriched uranium would be stored and swapped out throughout the voyage when the reactor fuel gets depleted. I can see that every 30-35 years or so a swap out will occur. The replacement ^{235}U will need to be kept from fissioning until needed. For a 10,000-year mission we may need to have almost 300 fuel swap outs!

This issue is serious, but fortunately there are several ways to address. One factor that may mitigate this problem is that the ^{235}U , even for an enriched reactor may only be 4-6% of the fuel, the rest being ^{238}U . To sustain a fission reaction, each neutron released by fission must initiate another fission reaction generating another neutron. As the amount of ^{235}U decreases in the fuel and additional decay products start to fill the reactor fuel, eventually the fission reaction is untenable, and the number of neutrons fall below the critical state. Once this happens the reaction is no longer critical, power drops off and the fuel needs to be changed out.

This means that the actual mass of the active ingredient- the ^{235}U - is actually very small so highly enriched fuels will be able to reduce our mass. Other options to mitigate the amount of fuel needed is that we recover and recycle our ^{235}U , because even though the ^{235}U is depleted while in operation, spent fuel still has most of its ^{235}U remaining. Another option is we will need to look at breeder reactors that create Plutonium to supplement the ^{235}U .

While there are many unresolved issues with regards to fuel swap outs and the actual capabilities of the fission power plant we have enough information to make a notional advanced reactor going forward with the following standard performance assumptions:

- Fission plant will put out 20w/kg or 20kW/mt electric.

- Power comes from ^{235}U . Based on the energy released by the splitting of ^{235}U we will consume about 1.05kg per day for 1GW of thermal energy.
- Assuming 33% thermal to electric conversion (this is optimistic but should be doable) we will consume about 3.15 kg per GWe per day. This works out to about 1150kg/year (1.15mt/yr) per 1 GWe. This is the mass of ^{235}U burned.
 - o If we used enriched Uranium, say about 5%, our fuel mass that would need to be changed out would be 23mt year or 2300mt per hundred years per GWe.
- We can store the resupply ^{235}U for future use without the ^{235}U being degraded
- Some level of Uranium reprocessing is done that will reduce the need for fresh fuel by 50%. Based on this we will assume that we consume about 1150mt of enriched U per GWe per 100 years.

To put this into a notional reactor we would have the following specifications:

- Baseline Reactor: 3GW_{th} or 1GWe or 1000MWe
- Total Reactor Mass: 50,000MT
- Fuel consumption: 23mt Enriched Fuel (5%) per year per 1000MWe. This works out to only about 1.15mt of ^{235}U .
- Enriched Fuel Resupply assumes 50% of ^{235}U from spent fuel can be recovered and reprocessed means 1150mt of fuel per 100years per GWe.

Recovery can be done via various methods... including types of breeder technology to make plutonium to supplement our power, or some processes of re-enrichment where we recycle the material and recover the unburned ^{235}U . Finally, by doubling the enrichment percentage (to 10%) we would half our replacement fuel mass.

Since deep space fission reactors are in such an immature state, many decades of engineering and design work will be required to achieve the performance required for a starship voyage. It is reasonable that far greater capabilities will be developed but for this we will likely have to wait for the 22nd century.

Summary and Conclusions

In chapter 7 and 8 we achieved a pretty high performance by having a two stage Starship. However, the useable payload was meager- only few tons, and the ships far too small to carry a crew. In all cases the voyage times were 10,000 plus years.

In this chapter we started looking at some out of the box solutions to help with our performance. The conclusions, while mixed, were that none of these options was a slam dunk.

- Beamed power for Electric Thruster starship. While freeing up more mass for payload, this method introduced other inefficiencies. Optimistically only 10% of the power beamed would be useable by the spacecraft and this meant that the power beaming station was 10X larger than that of the onboard Fission plant.
- Solar Sailing seems to be an option for small payloads, but the engineering challenges for a large 150mt Starship are substantial. To get reasonable velocities the solar sails need to be huge but

feather light. Furthermore, for needed performance the Starships need to approach very close to the sun. If truly strong and lightweight materials can be developed and developed in large quantities, then this may become a viable propulsion method.

- Solar Sailing with beamed propulsion combines the problem of beamed power for Electric Thruster, with the challenges of building large solar sails. The amount of photon energy required to provide the thrust for a large Starship is astronomical- several TJ for months at a time.

With that being said, there is no doubt that both the technology of beaming power or building solar sails needs to be kept in our toolbox. Building smaller solar sails of say 10 or 20kg is far less challenging than building a huge sail for a 150mt starship. If using beamed power, small solar sails will require 1/10,000th the power of the larger sail.

	Launch Mass Mo (t)	Empty Mass (t)	Mass Fraction	Specific Impulse	Exhaust Velocity (kps)	Final Startship Velocity (kps)	Type of Engine	Power	Mission Duration	Years to go 10LY	Comments
Saturn IXA	3,000	150	20.0	6000	58.9	176.6	Electric Ion/MPDT	Beamed/ Fission		16,989	50N; 2MW
Saturn IXB	3,000	150	20.0	9600	94.2	282.5	Electric Ion/HIPEP	Beamed/ Fission		10,618	54N; 80 HIPEP; 3.2MW; Power plant will weigh more than our m1
Saturn IXC	3,000	150	20.0	NA	?		Solar Sail	Beamed/ Fission			Depends on lightness ratio
Saturn IXD	3,000	150	20.0	100	1.0	3.0	Mass Driver	Fission		1,000,000	Low mass of starship prevents this from being viable

Chapter 10- Saturn X- 2080's- Developing a New Mission Profile

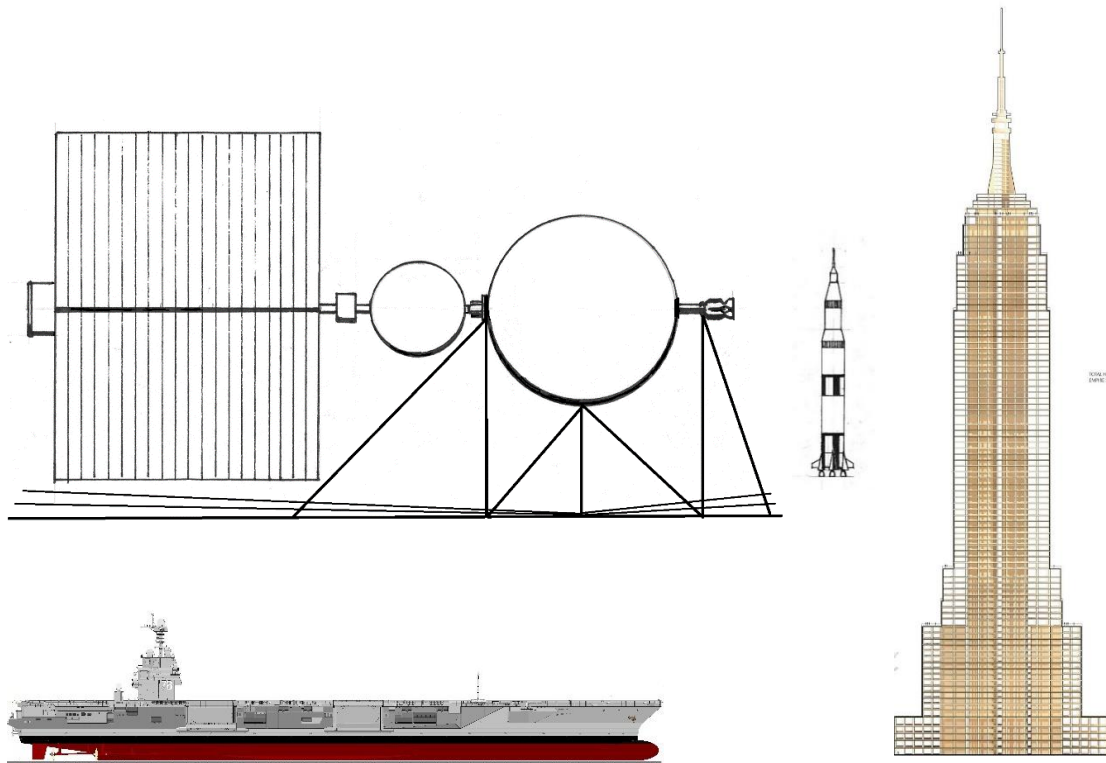


FIGURE 10-1 SATURN X; SATURN V; EMPIRE STATE BUILDING; USS GERALD FORD CVN78 (TO SCALE)

With the Saturn IX, we looked at alternative technologies to improve our performance. We considered eliminating the need for large fission reactors by providing power via beamed power. We also considered Solar Sails and Mass Drivers for propulsion. While beamed power offered some advantages it also introduced additional challenges. Solar Sails seemed too speculative from an engineering point of view and the Mass Driver was too massive and its performance too low to be a suitable substitute for a small starship propulsion system.

We are bumping up against the limits of available 21st century technology and the ability to drastically increase our performance is questionable. With all the starships considered we have been able to launch spacecraft into interstellar space, but the voyage times are on the order of several tens of thousands of years and our power supply would fail within a few centuries. Another issue that we have not even addressed is if we wanted to actually slow down at the target star!

Going forward we are not going to introduce any radically new technology... there are no other technologies out there that will be reasonably available over the next 50 years. We will however assume that the technologies we have already considered are refined even further. More importantly we will also look at an alternative mission profile over and above the single and two stage concepts we have already considered. Finally, we will start looking at larger starships. In Chapter 7 and 8 we considered a two-stage rocket to both leverage the performance of nuclear thermal engines during a powered maneuver and the higher mass efficiency (but low thrust) of the ion engine. Unfortunately, their usable payload became very small.

In this chapter we will take these ideas and build on the best of them. Our goal for this chapter will be:

- Target 300kps as our cruise speed. This will provide for a voyage time of about 10,000 years for 10 ly- or only 5,000 years to Alpha Centauri. Based on our previous chapters, it is about the most we can expect with our current technology. As we have seen 300kps is very difficult to obtain, but even this modest goal is only .1% of lightspeed.
- Plan for deceleration at the target star. Up until now, we have not even considered this because this makes our mission vastly more challenging. With the concepts discussed throughout this book this clearly is beyond our current technologies if we use them in a conventional mission and we will be required to think outside the box and restructure our mission. Our new mission architecture will be combining many of the techniques already discussed:
 - o Multistage
 - High thrust for Oberth Powered Maneuvers around the sun
 - Low thrust for accelerating once outside a majority of the suns influence
 - o Supply of reaction mass via revisiting the pellet proposal
 - o A decelerating mode on star arrival
- Allow our spacecraft to grow much larger to permit a viable size for Starship whose voyage time is 10,000 years.
- Our larger rocket will allow us to build a larger power supply and we will assume we are able to build a 20W/kg reactor.
- A starship that weighs ten or twenty times more than our previously considered starships is probably the largest that can be built with raw materials supplied by earth. Even with this sized ship, we need to start considering sourcing at least some of our raw materials from space.
- The larger size and effort will force us to consider a much larger space manufacturing capability than has heretofore been considered.

A Note on Deceleration

Adding the requirement for deceleration will substantially increase our challenges for a target velocity of 300kps. With a specific impulse of 10000 we will require a MR of 20 for both acceleration and deceleration. With an initial 3000 MT ship we would have a final empty and payload mass only $1/400^{\text{th}}$ of our starting mass- or 7500kg. This 7.5mt ship would have to have everything- payload, power supply, engines. The other 2,992,500 kg would be reaction mass.

Suppose we optimistically designed a rocket that could support a 10,000-year mission for a small crew with a much larger 3000mt m_1 . The initial rocket would now mass 1,200,000 mt. This is truly massive- on the order of 10x heavier than an aircraft carrier. With most of the ion engines providing a few newtons of force, acceleration alone would take longer than the voyage- the electric thruster would have to operate for many thousands of years. Additionally, our initial rocket mass is far too massive to be practically supplied from earth. We would need to source our materials from deep space- either the earth's moon and/or an asteroid or comet.

What our mass ratio needs to be of course will depend on our specific impulse. If we stick with 300 kps and our m_1 mass of 3000mt, we have the following scenarios:

Isp	Mass Ratio (outbound)	Mass Ratio with Deceleration	M ₀ weight Based on 3000 mt M ₁	
2000	164,000	26.9 billion	80.7 trillion mt	
5000	405	164,025	480 million mt	
6000	149	22,201	66.6 million mt	
7500	55	3025	9.08 million mt	
10000	20	400	1.2 million mt	Equivalent to 10 aircraft carriers

TABLE 10-1 MASS RATIO'S WITH DECELERATION AND 3000MT M₁

With these facts it becomes obvious that to be able to send a mission to the stars and stop at the target 10000 Specific Impulse is probably the minimum we can consider and that for a useable m₁ our m₀ will still be huge. Deceleration and its requirement for a massive spacecraft will require a whole new mission profile. Unfortunately, a 10000 specific impulse is about the most we can plan for.

Saturn XA - Electric Engine

Before we consider a new mission profile, let us take a brief look at what is likely the largest starship we could assemble in earth orbit from materials supplied from earth- a Saturn X with a m₀ of 30,000 mt and with a MR of 400.

Most of the Electric thrusters discussed use either Argon or Xenon. Xenon, as mentioned in Chapter 7, costs about \$1000 kg. Even if the cost was brought down to half, the cost for the fuel alone would be \$15 billion. Argon being much more plentiful would be only 1/1000 the cost. The problem we have now is that the density of Argon is fairly low, even when liquid (Table 7-2) - about half that of xenon and thus requiring a tank about 2x larger volume. To keep the size of the fuel tanks reasonable, we would need to keep the Argon at a chilly temperature of 87k (or -185C). Fortunately, our Starship will be in deep space for most of its journey, simplifying this challenge.

Whether we choose Xenon or Argon, it is unfortunate that the earth's atmosphere is the best source for these raw materials. Earlier we settled on launch costs at a reasonable but aggressive price of \$500 per kg target over the next half century. If this price is achieved, we have a cost to launch the fuel of \$14.25 billion- but if prices stayed in the \$1000 per kg range the costs would be at almost \$30billion. And this is only to bring up the fuel.

A starship will need to have several characteristics that are difficult for electric thrusters to overcome- high power requirements, low thrust, and finicky fuel. Both the VASIMR and MPDT may be able to provide a relatively high thrust but high only relative to electric thrust engines, when compared to a mass driver their thrust will be quite low. The VASIMR thruster appears to be further along in development with a 100kw version tested on the ground but even this engine needs more work. As far

as addressing finicky fuel, while usually using noble gasses most electrical thrust engines can use any element that can be ionized as reaction mass- however they are more reactive and will degrade the thruster's equipment. Versions of the MPDT engines have been proposed to operate on hydrogen. I would anticipate that while a hydrogen MPDT engine would have a very high specific impulse, it would have low thrust and fuel flow. Since it is not a noble gas it will cause much more erosion to the engine elements and, as we have seen, storing hydrogen (especially for the decades or centuries it will be needed) is a challenge in of itself, requiring very low temperatures, large volume for storage and very tight tolerances to prevent leakage. We could consider generating hydrogen when needed by the electrolysis of water, but this introduces additional problems- first you need to separate the hydrogen from the oxygen which will require a lot of power. Then you would dispose of the waste oxygen- which accounts for almost 90% of the mass of the water. You would be getting thrust from only 1/9th of your fuel... the rest of the mass is unneeded.

Note that the easiest alternative to addressing our mass challenges is reducing our speed. If we consider a mass ratio of only 10 to one for each phase of our mission, we reduce our mass ratio from 400 to 100. The compromise is a slower speed- with a 10000 sec engine we would now be looking at a speed of only 230kps. In this scenario, the penalty is a voyage time about 30% longer. This may be a viable plan B.

For now, let us look at a vessel with a 30,000mt m_0 and 75mt m_1 . Could our 75 mt be massive enough to contain our structure, payload, engines and power supply? This looks to be a difficult proposition. Let us look at how much power we would need ...

Power Requirements

The power requirement of a large electric engine will be substantial. What the best engine is will only be determined with further research and engineering development. Key requirements will be incredible reliability, and extremely long lifespan and exceptional performance. Both the VASMR or MPDT are moderately far along in development and provided a fairly high thrust, but their specific impulse is around 5-6000seconds- though both should be able to be improved upon. For the Saturn X we have settled on a minimum specific impulse of 10,000.

Using the advanced HiPEP engine from Chapter 9, to generate about 27N of force requires about 1.6MW of power. If we wanted to raise this to about 108N we would require about 6.4MW. Furthermore, the HiPEP is published as having a specific impulse of about 9600 so any increase to 10,000 will require additional power but for simplicity we will keep our power requirements as shown in Table 7-1. Keep in mind that this is not an optimum engine... the current designs posted thrust of 670mN means that for us to raise our thrust to 108N we will require 160 engines!

If we round down our numbers and target 25N, we would have a power plant that weighs 80mt. This is already more than our 75mt allocation. We can decrease our power requirements by decreasing our thrust even more.

Lets assume we stick with our current thrust. Rearranging the terms in equation 3-3 and calculating for mass flow:

$$\text{Equation 10-1 } \dot{m} = \frac{F_{thrust}}{v_e}$$

$$\dot{m} = \frac{25nt}{100,000mps}$$

$$\dot{m} = .00025kg \text{ sec}$$

With our starting mass at 30,000mt, after the acceleration is complete, we will be down to 1500mt. We will need to expend 28,500mt of mass. At the calculated mass flow rate it will take 114 billion seconds to consume our fuel- or about 3615 years.

Our deceleration period will be far less- only 1/20th of this time- or 180 years.

We could slightly decrease our thrust to get our power plant below our 75mt weight limit, but still need a large mass for our fuel tank and payload. It is obvious that nuclear power in this case will work only if we increase our acceleration times by decreasing our thrust even further.

Added to these challenges we still have the issue of the powerplant lasting for thousands of years. Without replacement cores of enriched Uranium, this problem is unavoidable, inevitable, and still unsolved. Our replacement Uranium, even with efficient reprocessing, will still require new fuel which will add to our weight issues.

But we have an even more serious issue- the low thrust provided by these engines still means we will not be able to exit the solar system for many centuries so we will still require a two-stage ship for the outbound journey as we investigated in Chapter 7 and 8.

Acceleration Challenges

The low thrust of our Electric Thrusters is a problem regardless of our Starship size. Larger rockets need large thrust which requires a larger and heavier power supply. Leaving aside the issue of having an electric thruster starship being able to escape the sun's gravity well, the bottom line is that our low thrust leads to extraordinarily slow accelerations- especially for the outbound acceleration portion of our voyage. This needs to be addressed as our rockets get larger. Let us look at some variations assuming a 10,000 sec Isp but varying our mass and thrust and building very large starships with a MR of 400:

Mass m ₀ /m ₁ (mt)	Mass Flow (kg/sec)	Thrust (nt)	Power Required	Power Plant mass mt (20W/kg)	OB Acceleration Times	Deceleration Times (years)	Comments
600,000/ 1500	.001	100	16mW	1600	18,050	950	Assume 10W/kg
600,000/ 1500	.001	100	16mW	800	18,050	950	Assume 20W/kg

600,000/ 1500	.01	1000	160mW	8000	1,850	95	Assume 20W/kg
10,000,000/ 25,000	.01	1000	160mW	8000	28,700	1506	Assume 20W/kg
10,000,000/ 25,000	.1	10000	1.6GW	80,000	2,870	151	Assume 20W/kg
50,000,000/ 125,000	.1	10000	1.6GW	80,000	14,350	718	Assume 20W/kg
50,000,000/ 125,000	1	100000	8GW	400,000	1,435	72	Assume 20W/kg

TABLE 10-2 POWER AND STARSHIP MASS FOR 10000SEC SPECIFIC IMPULSE, 300KPS CRUISE SPEED; ACCELERATION AND DECELERATION (MR 400)

All of these Starship scenarios are much larger than what we have so far considered. What this chart tells us is that for our smallest practical starship, netting 600,000mt, we need at least 1000nt of thrust. In the first example I looked at a power plant that put out only 10W/kg of mass and the power plant turned out to be more than our m1. We cannot make a 10W/kg powerplant work even with a leisurely 18,000-year outbound acceleration. Furthermore, even with 20W/kg powerplant, if we make our power plant about 55% of our m1 mass, our acceleration times are about 18,000 years.

Clearly we need to do one or several of the following:

- Creating lightweight fission reactors is a requirement of our mission if we are going with electric thrusters. 20W/kg can work but uses up most of our m1 mass. In addition, this does not include the mass of the extra Uranium to refuel. Our Electric thrusters will need full power for thousands of years. Getting more power per kg of power supply mass is critical.
- Consider the beamed power option from Chapter 9.
- Boost the efficiency of our propulsion system in order to get the acceleration periods down without increasing our power consumption. As we shall see this is limited by physics and improvements may not be substantial.
- Reduce our ship velocity to 230kps which will lower our mass ratio to 10 for both acceleration and deceleration for a total MR of 1000. This will also reduce the time needed for acceleration.
- We still have not addressed the need to get our starship out of the sun's gravity well so the electric thrusters can be effective.

It would seem that building a rocket with the capability of both accelerating and decelerating to a target star with current and near-term technology is just too daunting. We are reaching a dead end. We need to come up with alternate ideas to get to the stars.

Saturn XB- Collecting Mass Enroute

In science fiction movies, fuel never seems to be much of a problem. If the crew runs out of fuel, a small shot of antimatter or a swap out of di-lithium crystals solve the problem. But as we have seen with the tyranny of the rocket equations, fuel is not the biggest issue- reaction mass is- something which science fiction usually ignores. The need for a large amount of reaction mass drives the starship m_0 to a massive size, which in turn slows its acceleration and makes the amount of power needed ever greater. With Chemical engines the fuel serves both as the source of energy, and the reaction mass. With nuclear thermal, the nuclear fuel heats up our reaction mass. With Nuclear Electric power, nuclear fuel provides the energy to accelerate the reaction mass indirectly- whether the reaction mass is plasma or slugs accelerated down a mass driver.

Jet aircraft travel thousands of kilometers and the fuel is usually less than 25% of the aircraft's mass. How are they able to do this? The answer is that they are not carrying their reaction mass with them but are imparting acceleration to the air that is lying all around them.

Can we do the same thing? Just as with the beamed power option where we are able to reduce the mass of our starship by removing our powerplant and putting it on a distant asteroid or satellite, can we reduce our mass by having our reaction mass "floating" in space to be picked up as needed? Suppose we could essentially pick up our reaction mass enroute like a jet engine?

The answer is yes. I propose a variant of the pellet scenario where the starship, instead of using the momentum of impacting pellets to accelerate our vehicle, instead uses these pellets as reaction mass that the engine picks up and accelerates the way a jet engine accelerates the air around it.

In a jet engine, air enters an inlet and is accelerated out the back- mostly by a turbofan. A small part of this air is combined with fuel and burned, primarily to provide energy to spin the turbofan but with the remaining exhaust also providing a small amount of thrust. Regardless, most of the thrust on a turbofan jet engine comes from the acceleration of huge masses of air through the turbofan, and not much from the mass of the burned fuel. This is radically different than in our rocket where the "air (oxygen)" has to be carried with us and the combined mass of the oxygen and burned fuel provides all the thrust.

In this new scenario our starship come across pellets or "packets" of mass floating in space at around the same speed as our rocket, captures this mass and either directly accelerates this mass for propulsion, like a mass driver, or breaks down the packets into ions and accelerates with an ion engine. As opposed to the pellet proposal in Chapter 9 the pellets are not used to impart energy to the Starship, but instead are there to provide reaction mass. We now have a spacecraft more in line with what Science Fiction usually has- a Starship that carries no reaction mass.

Let's work backwards and see what our performance could be with this scenario. Our rocket will carry no reaction mass but instead will encounter its reaction mass as it travels through space. In this analysis we will assume some sort of electric thruster. Instead of carrying our fuel we pick up our fuel along the way. Now we do not need have a 30,000 MT rocket to accelerate but only 1,500 MT. If we keep our assumption of a 100nt engine but keep our mass still at 1500mt what would our performance be?

$$a = \frac{F}{m} = \frac{100nt}{1,500,000kg} = 0.0000667$$

If we shoot for a target speed of 300kps it will take our 1500 mt rocket:

$$t = \frac{\Delta v}{a} = \frac{300,000}{.0000667} = 4,500,000,000 \text{ sec}$$

or about 142 years of acceleration. This is a huge improvement over the Saturn XA.

Our reaction mass will consist of larger packets spaced along the path (either in front of our ship in which case our ship would slowly gain on them and scope them up- or behind our ship where the packets would slowly catch up to our ship and get recovered). Our starship would pick up the packets (we will consider how to do this in Chapter 11) and then accelerate them for thrust. We will use the term packet from now on to distinguish this method from the pellet version discussed earlier. Later in the chapter we will also discuss the requirements for the packet launcher, but for now we will assume a large solar system fixed mass driver that projects these packets into our path. The nature of the packets and the “mass” would have to be determined by a thorough engineering analysis.

Based on our calculations earlier, for a Force of 100nt we would accelerate .001kg of reaction mass per second. This works out to 3.6 kg per hour. We can imagine encountering a 86.4kg of material in a few packets a day. This will be considerably more complicated in practice- for instance if using hydrogen, a tank of compressed liquid hydrogen will have its own considerable mass so the actual packet encountered might have the container mass 50% of the packet. If our packet were shipped as Water, we would need to have a 215kg block of ice to be able to extract our 36 kg of hydrogen. Using Xenon or Argon would eliminate the need to separate hydrogen from oxygen, but now all your reaction mass would likely have to be lifted from the earth and stored in a pressurized sealed vessel, which makes our refueling not very efficient as the containers are essentially dead weight and not able to be used in the ion or plasma engines.

In many ways the packet supply technique is equivalent to the laser beamed power schemes we have looked at- except instead of beaming power to our starship we are “beaming” mass. Indeed, because of the large mass of the starship, beamed mass turns out to be more of a critical technology and game changer than beamed power.

Deceleration on Arrival

With the Saturn XA we first attempted to address deceleration but quickly found out the challenges are substantial. Even with a reasonable 20:1 mass ratio for both acceleration and deceleration, our total MR at the beginning of our mission would be 400:1.

With the use of refueling enroute we now have a way around these problems. If on the way out we used the collected packets for reaction mass, we could again get down to a peak mass ratio of 20:1 which would only be needed for deceleration. In theory, it would be great if we could use the same technique of refueling enroute for our decelerate but this would not be practical for several reasons. First, the deceleration will be occurring much further from the solar system- how would we get the packets there? Any mass used to slow down would have to be launched many thousands of years earlier than our mission start so that by the time our rocket needed to decelerate the packets would arrive at our

target star nearly 10 light years away. In addition, the last packet intercepted while we slowed down would itself be traveling very slowly which means they would have had to be the first packet launched and at the slowest speed. If we assumed the last packet intercepted before we arrive at the star is only traveling at 10kps, and we are 10 lightyears away, this packet would have had to been launched nearly 100,000 years ago.

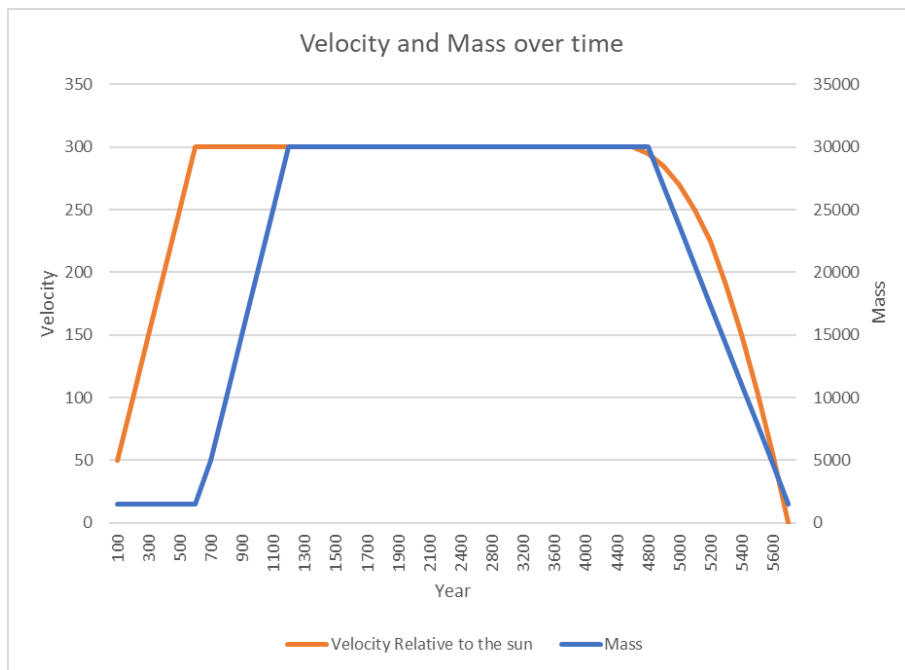


FIGURE 10-2 SAMPLE VELOCITY AND MASS CHART FOR ENROUTE REFUELING

Picking up reaction mass is a game changer- it reduces our m_1 to only 1500mt and permits a much faster acceleration. The packet technique has another tremendous additional advantage- after our initial acceleration phase, we can continue to receive packets to resupply our ship and use it to enlarge our ship or replace materials that were consumed (like reactor fuel). This has the advantage of keeping our initial starting mass of our

Saturn X low while we accelerate, but permits us to accumulate reaction mass for our deceleration.

If our starship was at its 300kps target speed, we could continue to get supplies launched at 300.03kps... or packets arriving at 30mps. With a much smaller ship which will make the initial acceleration phase much faster, and after the initial acceleration phase we would enter a resupply phase to improve on and enlarge our small ship as well as to pick up mass for our deceleration phase. A notional mission profile is shown in Fig 10-2. Now our 1500mt m_1 rockets builds up its mass to 30000mt m_0 which will be used for deceleration. In this example our starship starts with an initial velocity of 50kpi, accelerates by picking up enroute packets to 300kpi, then, accumulates mass that will be needed to decelerate on target star arrival. The values in this graph are representative for illustration purposes – we will do a more accurate engineering analysis later in this book to arrive at more realistic numbers.

Saturn XC- Three Stage Hybrid

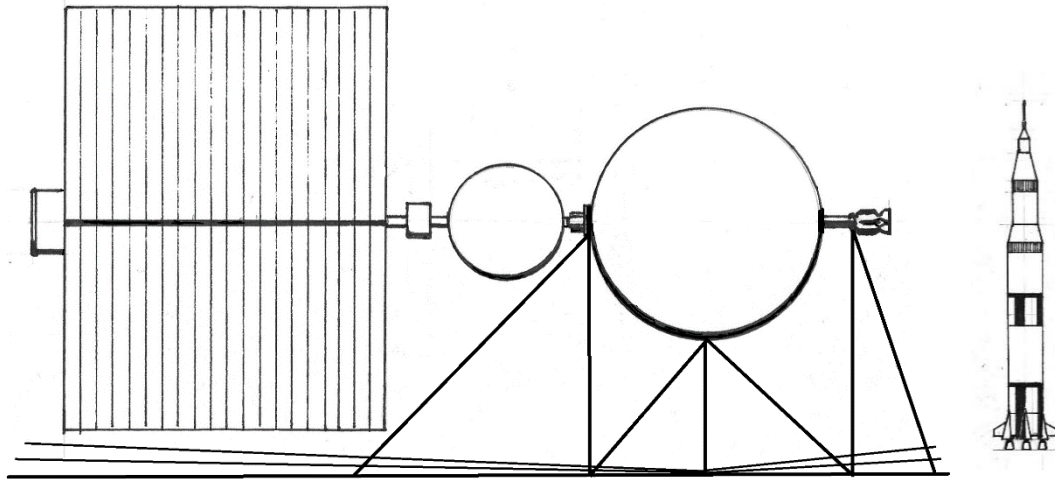


FIGURE 10-3 SATURN XC AND SATURN V (TO SCALE)

Supplying mass enroute tremendously simplifies our deceleration issue by reducing our starting mass by a factor of twenty. Without this option, our best option looks to be a variation of an aggressive 3 radii powered maneuver around the sun which gets us to 120kps as with our Saturn VIIC. At 120kps we get to the nearest stars in about 25,000 years- perhaps acceptable to our colonizers. However, by adding the requirement to decelerate our mass becomes so large that our starships sun powered maneuver would be difficult to achieve. With enroute resupply, we reduce our starting rocket mass for our m_0 by 20x. With a Saturn XC we will combine three different ideas:

- one stage to have a high thrust engine to perform a sun diver powered maneuver to start us on our way on a hyperbolic orbit.
- a second stage with a high Specific Impulse but low thrust engine for the interstellar voyage. Material for this reaction mass will be picked up enroute.
- A third stage where reaction mass is picked up after we reached our cruise speed. This reaction mass will be used for our deceleration. This third stage is likely to use the same propulsion system as was used in the second stage.

Let's take a first cut at coming up with a characteristic performance for a Saturn XC:

- A first stage with a high thrust engine (either Nuclear Thermal or conventional) to break us out of the Sun's Orbit. For now, the large dV we are targeting implies a Nuclear Thermal with a MR of 7.5.
- A second stage Ion Engine of 108N with a Specific Impulse of 10,000 where mass is picked up and ejected enroute
- Peak Velocity is 300kps
- Additional mass will get picked up for our deceleration phase. We will pick up enough mass to give us a MR of 20 of the final arrival m_1 .
- A third stage consists of restarting the Ion engine to decelerate on arrival at the target star.

- Let us assume that we need 6.4 MW minimum to power our 108N engines. The mass of the power supply has already been determined to be 320mt. Because of the need to have a fuel supply last for at least a few centuries we will assume that replacement fuel and such will double the mass to 640mt. We will calculate a more reasonable number later.

To determine our starting mass we need to work backwards from our ending mass during the outbound acceleration. If we assume that 1500mt will be sufficient for our ending mass at the target star we will need to peak our mass out at 30,000mt for our MR of 20. For deceleration the electric thrusters with a specific impulse of 10,000sec will be exclusively used.

For the initial outbound acceleration, we use an identical approach that we took for the Saturn VIIC but will reduce our mass ratio slightly so we can have a larger m_1 . A nuclear thermal engine and a MR of 7.5 provides a total 20kps dV of which 10kps would be used for a powered maneuver around the sun (at 3 solar radii), we would get a speed of 80kps on Stage 1 Burn Out. This performance will be slightly worse than the Saturn VIIC since with that starship we assumed a MR of 10 with 23kps dV. The reduced performance of our Saturn XC will be reflected in a longer voyage time to Jupiter. The First Stage at rocket burnout target is a 1500mt payload second stage but it itself will also have its own tanks and rocket engines- so the 1500mt final mass does not include the empty first stage LH tank and engines- as well as some sort of solar shield to protect it during its close approach. Therefore, we will have to bump up the first stage empty mass (see Table 10-3) to 2,000mt. Using 2000mt final mass and a MR of 7.5 the mass of hydrogen works out to 13,000mt.

At first stage burnout the second stage mass will be 1500mt and contains our nuclear power supply, payload, electric thrusters and fuel tank. The second stage will need to gain another 220kps with our electric thrusters but will refuel enroute, so it will not need to carry any fuel.

This hydrogen tank is 123x more than our SS tank stored. Converting this to volume we would need a spherical tank about 70.7m in diameter with a surface area of 15708m². Using our quick rule of thumb of 17.5kg per square meter of tank, our tank alone would weigh 274,890kg, or 275mt⁷. To be on the safe side and to be able to handle the mass of the fuel tank, we will assume that at the end of our first stage burnout our spacecraft will weight 2000mt. This means to keep our MR at 7.5 we will start out at 15,000 mt. Our first stage, including empty fuel tank and spent nuclear engines will be 500mt and will be dropped.

After the first stage is exhausted and the large tank and engines dropped, our vessel will be down to 1500mt. We will begin to intercept packets launched by our Mega Mass Driver back in the solar system, and using this material, accelerate our ship.

For simplicity, let's round some of our numbers and assume our engine mass flow rate is .001kg per second. With a specific impulse of 10,000 our thrust will be

$$F_{thrust} = \dot{m}v_e = .001(100,000) = 100nt$$

To get our 1500mt spacecraft to increase its speed by 220kps will take a long time:

⁷ This is not accurate, and a better engineering analysis will need to be performed. As mentioned before, as spherical tanks get larger the force caused by the pressurized Hydrogen also will increase necessitating a stronger (thicker) and heavier tank. We will look at developing a more accurate mass for large tanks later in this book.

$$a = \frac{F}{m} = \frac{100}{1,500,000} = 6.667 \times 10^{-5} \text{mps}^2$$

$$t = \frac{\Delta v}{a} = \frac{220000}{6.667 \times 10^{-5}} = 3,300,000,000 \text{sec} = 104.6 \text{ years}$$

After we achieve our target speed, we will continue to accumulate mass. If we assume that our final arrival mass is 1500mt, then we will need to accumulate 28,500mt of reaction mass to be able to decelerate from 300kps down to a speed slow enough to go into orbit around our target star. Between the acceleration and deceleration phase we need a lot of reaction mass. Because of this for now I would elect to use the more plentiful Argon as our fuel. Using a density of 1395kg/m³ we will need a spherical tank of 20,430m³ or a sphere about 34m in diameter.

	First Stage (mt)	Second Stage- Enroute Refueling (mt)	Deceleration (refueled enroute) (mt)	Payload	Comments
M_{structure}	500 (Fuel tank of 71m dia will mass 275)	1180	180 (Fuel Tank will be 34m dia and mass 63mt)	1180	500mt empty first stage (including Nuclear Rocket, Tank and Sunshield) will be dropped
Payload	1180		1000		
M_{Power Supply}	320	320	320	320	
M_{Propellant}	13000	0	28,500		
M_{total}	15000	1500	30000	1500	
M_{empty (after fuel)}	2000				
Mass Fraction	15,000/2000 = 7.5	Refueling in flight	3000/1500= 20		
Isp	1000	10000	10000		
dV kps	80	220	300		

TABLE 10-3 THREE STAGE SATURN XC

Using our mass flow rate of .001kg/sec, our deceleration will take 2.85 billion seconds to decelerate- or about 904 years.

The next big area to look at is how much fuel will be consumed. Our early rule of thumb is that enriched Uranium generating 1MW_e per year consumes 23kg of enriched Uranium fuel. To generate 6.4MW_e we would consume 150kg of enriched fuel per year. We have a little more than 1000 years of acceleration

and deceleration requiring 6.4MW_e of power ⁸. We would need about 150MT of fuel for these portions of the voyage. The coasting portion would consume the base load of only 500kWe for about 9000years. All told, the fuel portion would mass about 250mt- a manageable number.

If necessary we could reduce this by either using a more highly enriched fuel, some level of shipboard reprocessing of fuel to recover the unused $^{235}\text{Uranium}$ or use the packet resupply method to supply extra fuel.

Finally, as our power requirements grow, we will need to have large cooling radiators for our reactors. In Chapter 8 we calculated that we would need 1836m^2 for a 3MW thermal reactor. For a 7MW_e we will need a 21MW_t reactor. This works out to a radiator 12852m^2 , or a square radiator about 113m on a side.

Summary and Conclusions

We now have the outlines of a starship and a mission profile. We are converging on a stripped-down ship that nevertheless is going to be heavier than 1500mt m_1 . This ship will have two stages on outbound- one with high thrust rockets to break free from the sun's gravity, and the other a low thrust but efficient rocket to continue acceleration by picking up fuel in packets which provide reaction mass (either for an electric thruster or a mass driver). Once the ship gets up to its target speed then it will continue to accumulate mass until it reaches a 20 MR. We seem to have a workable system and mission profile with several caveats- the main ones being:

- Can we develop a mass driver to rapidly launch packets at 300kps with the required accuracy for our starship to pick up? It is obvious that this is the key upon which this mission depends.
- Develop a method for our starship to be able to retrieve these packets.
- Determine the required m_1 size. The complexity and length of the mission imply we will need a much larger ship than the 1500m_1 used in this chapter- but how much larger? Is the mission profile scalable? The three items below will be further addressed in Chapter 12.
 - o Add more rigor to our Payload Mass calculations including habitation size
 - o Add more rigor to our Power Supply mass calculations.
 - o Add more rigor to our propulsion system design and mass
- Identify what supplies and raw materials will be needed to ensure the starship will be functioning (instruments, power supply) for 10,000 years?
- What is the mission? Until we specify this, the size will be undeterminable.

In Chapter 11 we will look compare the performance of a large electric thrust propulsion vs a Mass Driver, the challenges of building large mass drivers, and the technology as well as the feasibility of a very large Mega Mass driver to launch packets accurately and fast enough to supply our ship. We will also fill in some of our logistics of resupply and settle on our Starship propulsion system.

⁸ We would actually need more as some would be needed for our crew and payload. For a small crew (let's say a dozen in a small habitation module) likely only 500kwe would be sufficient and this would be the baseload throughout the mission which would raise our peak power requirements to about 7MW.

With a 10,000-year mission we would need to colonize the star on arrival. An automated mission of this duration would not be practical. A 10,000-year mission will require extensive repair capabilities and a lot of redundancies which will increase our mass- as well as drive the requirement for a crew. We will therefore need to consider a much larger starship that will be able to colonize. How big will this need to be and how will this affect our mission profile? That will be the topic for chapter 12.

	Launch Mass Mo (t)	Empty Mass (t)	Mass Fraction	Specific Impulse	Exhaust Velocity (kps)	Final Startship Velocity (kps)	Type of Engine	Power	Mission Duration	Years to go 10LY	Comments
Saturn XA	300,000	750	400.0	10,000	98.1	300.0	Electric/ Ion	Advanced Fission			May not escape the suns gravity; 19000 years of acceleration/ deceleration
Saturn XB	30,000	3,000	10.0	10,000	98.1	230.0	Ion	Advanced Fission		10,000	Will have difficulty escaping suns gravity; Enroute Refueling
Saturn XC	30,000	1,500	20.0	1,000/ 10,000	9.8/98	300.0	Nuclear Thermal/Ion Engine	Advanced Fission		10,000	3 Stage; Enroute Refueling

Chapter 11- Designing and Building- 2080's

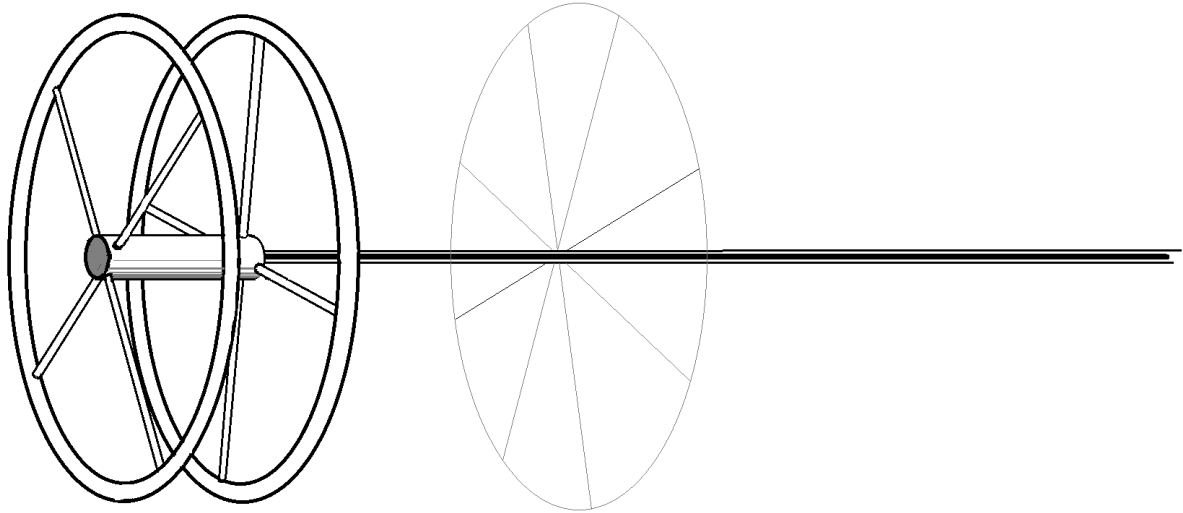


FIGURE 11-1 NOTIONAL STARSHIP- SATURN C TORI, PACKET CAPTURE NET AND MASS DRIVER

We have a broad outline for a Starship which we will call Saturn C. We are going to start with a much larger but still unknown m_1 and will pick up material enroute. However, as pointed out in the acceleration challenges in Chapter 10, larger ships are a challenge for electric thrusters. We need to see what the limitations of the Electric Thrusters are and compare them to the strengths and weaknesses of our old friend, the mass driver.

Comparison of Electric vs Mass Driver on deceleration

To accurately compare the electric thruster vs the mass driver let us set up some parameters so that we can compare apples to apples. Let us look at a 10,000 second specific impulse with a 100nt thrust for both the Electric thruster and Mass Driver. Our starting m_1 mass will be the same but the number and nature of the enroute packets will be very different depending on what thrust system we go with.

Electric Thruster

Earlier we introduced a notional Advanced Electrical Thruster (AET) for the Saturn XA. It had the following specifications.

Isp: 10,000sec

Thrust: 100nt

Power: 6.4MW (power supply would weigh 320mt)- adjusted to 9MW⁹

Mass Flow: .001kg/sec (86.4kg per day)

Mass of Electrical Engines: Unknown but relatively light. However larger sized Electric Thruster, like VASIMR, require cooling. A 200kw VASIMR engine needs radiators to reject about 70.5kw of heat (Andres & Nikolai, The VASIRM Engine: Benefits, Drawback, and Technological Challenges, 2011). The International Space Station has an active Thermal Control System of an equivalent capacity that weighs 54 MT. Crudely extrapolating our 100nt thrust engine as being 20x larger than the baseline VASIMR, we could estimate that the cooling system alone might be 2000mt. Coming up with an accurate mass for Electric Thrust engines is difficult since these thrusters are several orders of magnitude larger than anything previously built, but some numbers need to be used if only to reflect that high power engines do have associated weight over and above just that of the engine. I don't believe these coolers will be as heavy as the mass as the power supply's 20w/kg. Going forward, I will assume that electric thrust engines weigh only ½ that of our power supply per watt handled- or 40w/kg. This is much lighter than that on the ISS but reflects optimistic engineering development and the fact that the deep space environment (away from the heat of the sun and radiant heat from the earth) should allow for a more efficient cooling.

When comparing the Electric Thrusters to the Mass driver, considerable uncertainty on the selection of fuel makes a reliable comparison difficult. Almost any element can be used for an electric thruster but as we have discussed noble gases and items that can be stored as a liquid are preferred. If we use Argon or Xenon, how much of our packet mass will be the container/bucket and how much the actual reaction mass? Would it be better to ship Argon or Xenon as compressed liquids or as a solid? Suppose we use Mercury? The same problem exists if we choose Hydrogen. Will hydrogen be shipped compressed or shipped as water? To reduce the number of packet configurations we will only look at a few scenarios for 20kg packets and make some rough estimates on the container/bucket size:

Type of Engine	Container Content	Container/ Bucket Mass	Reaction Mass/ Supplies	Useable Reaction Mass	Engine Efficiency (percent useable for reaction mass)	Comments
Mass Driver	Water	10	10	20	100%	
Hydrogen Electric Engine	Water	10	10	1.67	8.3%	H Ion Engine; 1/9 th of water; water shipped as solid ice
Hydrogen Electric Engine	Hydrogen (LH)	15	5	5	25%	Shipped as liquid

⁹ Note that the 6.25MW for 100N which was derived from published performance but assumes 80% efficiency. This is not realistic. Electric thrusters appear to be closer to 50% efficient. To account for this I have adjusted the power required for electric thrusters down across the board. Going forward I have used 8.53MW per 100nt.

Argon/ Xenon Electric Engine	Argon/ Xenon	10	10	10	50%	Shipped as Liquid

TABLE 11-1 VARIOUS PACKET CONFIGURATIONS IF USED BY A MASS DRIVER FOR PROPULSION

Even though I had to make some crude estimates on the mass of the bucket/container, a packet supplies mission will be most efficient if using a mass driver regardless of the mass of the container. A mass driver propelled starship will use ½ the number of packets of a Argon/Xenon engine for an equivalent reaction mass, ¼ the requirements of a LH supplied hydrogen ion engine, and 1/12th the packets of a water supplied hydrogen ion engine that uses electrolysis for separation of the hydrogen.

Mass Driver

So, would a mass driver be more effective propulsion for our starship? In general, a mass driver will generate much more thrust and may generate this thrust a bit more efficiently than an electric thruster. The biggest drawback is that for a high specific impulse thruster the mass penalty is substantial.

Suppose we had a powerful mass driver that could accelerate a .1kg mass at 10,000g. This would provide 10,000nt of force. If we fired one .1kg projectile every 100 sec- for a total of 86.4kg per day we'd have an average thrust of 100nt. How much power is needed to accelerate .1kg to 100,000 mps?

Power= ½ (.1)100,000² = 500 million joules or 500 MW.

Like our acceleration and time calculations this is how much power is needed to accelerate a .1kg mass and would be an accurate calculation if we had this mass flow per second. A more appropriate way to calculate this is to consider that we are only firing .1kg once every hundred seconds or, on average .001kg per second which leads to 5MW of power.

The instantaneous power needed for our 1 second pulse would be saved up via capacitors or some other storage device during the 99 seconds between each firing. Using 5MW as the power requirement we would need only a 250mt power supply if we use 20W/kg. Note that this assumes 100% efficiency of conversion from electrical power to motive power... which is not realistic. In reality a mass driver will likely be similar to a electric thrust engine. In one report, the target efficiency was 80% (Kolm, L5 News: Mass Driver Update, 1980). Let us use this number for both the electric thruster and mass driver. Therefore, we will need 6.25MW for our engine.

Traditionally, our mass driver was crippled by its excessive length and therefore weight. At 10,000g the mass would accelerate to the effective 100,000mps velocity in 1 sec and our mass driver would be 50km long. Since our projectiles are only .1kg vs the 1kg previously considered but our acceleration is 10x greater, we will assume that our MD mass per meter remains 500 kg/m. It is possible that the small aperture for a .1kg reaction mass would be able to reduce the size of the coils enough to save some weight but I am not convinced. Using our 500kg/m estimate we come up with a total mass of 25,000mt.

Keep in mind is that as opposed to our electric thrusters that are operating continuously, our 10000sec mass driver is only operating 1/100th of the time. This implies that given more power and more reaction mass packets we could ramp up or thrust considerably without increasing the mass of our engine. With the ion engine to increase our thrust by 10x we would need 10x more engines.

Let us look at some hypothetical configurations. There are many independent variables. Table 11-2 makes some assumptions in an attempt to restrict the variables but still come up with some meaningful comparisons. I took two propulsion systems... the electric thruster and the mass driver. Our target speed is 300kps for a journey time of 10000 years. I show two specific impulse examples for the two systems... one a 6000sec engine and the others a 10,000sec engine. I assume that the payload is 1500mt.

Propulsion Type	Electric Thrusters				Mass Driver			
Thrust (nt)	100	100	1,000	10,000	100	100	1,000	10,000
Specific Impulse (sec)	6,000	10,000	10,000	10,000	6,000	10,000	10,000	10,000
Ve	60,000	100,000	100,000	100,000	60,000	100,000	100,000	100,000
Power (mW)	5	9	85	853	4	6	64	640
Spacecraft Payload	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Engine Mass	133	213	2,133	21,333	13,500	25,000	25,000	25,000
Power Supply Mass	267	427	4,267	42,667	200	320	3,200	32,000
Power Supply Refuel (10000 year mission)	1,227	1,963	19,627	196,267	920	1,472	14,720	147,200
m1 light (mt)	1,900	1,740	7,900	65,500	15,200	26,820	29,700	58,500
m1 with Fuel Rplacements (mt)	3,127	4,103	27,527	261,767	16,120	28,292	44,420	205,700
m2 (mt)	462,747	82,053	550,533	5,235,333	2,385,760	565,840	888,400	4,114,000
Fuel Flow (kg/sec)	1.67E-03	1.00E-03	1.00E-02	1.00E-01	1.67E-03	1.00E-03	1.00E-02	1.00E-01
Fuel Flow daily (electric thruster 80% effi)	180	108	1,080	10,800	144	86	864	8,640
Acceleration	5.26E-05	5.75E-05	0.000126582	0.000152672	6.57895E-06	3.72856E-06	3.367E-05	0.00017094
Seconds of Acceleration to 300kps	5.700E+09	5.220E+09	2.370E+09	1.965E+09	4.560E+10	8.046E+10	8.910E+09	1.755E+09
Years of Acceleration (300kps)	180.75	166	75	62	1,446	2,551	283	56
Reaction Mass	11,875,000	6,525,000	29,625,000	245,625,000	76,000,000	80,460,000	89,100,000	175,500,000
Packet efficiency	50.00%	50.00%	50.00%	50.00%	100.00%	100.00%	100.00%	100.00%
Number of Packets (acceleration)	1,187,500	652,500	2,962,500	24,562,500	3,800,000	4,023,000	4,455,000	8,775,000
Number of Packets for deceleration	46,274,667	8,205,333	55,053,333	523,533,333	119,288,000	28,292,000	44,420,000	205,700,000
Total Packets	47,462,167	8,857,833	58,015,833	548,095,833	123,088,000	32,315,000	48,875,000	214,475,000

TABLE 11-2 PERFORMANCE COMPARISONS WITH 1500MT PAYLOAD

There is a lot of information to unpack in this table and a lot of variables that had to be selected in order to be able to arrive at numbers that can be compared. Our payload of 1500mt is far too small for a manned mission but is a starting point- in Chapter 12 we will develop a more reasonable mass. To this payload mass I add the engine mass, and the power supply needed for our engines. The mass of the power supply was calculated based on the Electric Thrusters being about 75% of the efficiency of the MD. I have not included the refuel mass in the m₁ total since the intent is that this fuel will be provided to the starship via packets as needed, primarily after the starship acceleration period. In addition, two other conflicting factors have not been included in the power supply estimates:

- The power requirement during acceleration will be higher than what is indicated. The crew will be needing power for heat, light, the growing of food etc. and this will need to be added to the power needed for our engines. We will determine how much power is needed in Chapter 12 once we determine the size of our payload and crew as well as the thrust of our engines.
- Offsetting this the extra power being needed for the acceleration phase, once the acceleration phase is complete, we only have power needed for cruise. This means we will need less fuel during the majority of the voyage. Until we estimate the size and power requirements of our crew in Chapter 12 we do not have enough information to adjust this table.

Reaction mass is the mass needed to accelerate our m₁ to 300kps. Packet efficiency is an expression to factor in the percentage of each packet mass that arrives is useable for reaction mass. In the case of the mass driver, it is assumed that the entire packet can be used for reaction mass. Table 11-1 shows the assumptions that I made for the various configurations. With the electric thrusters, it is assumed that

only 50% of the arriving packet mass will be able to be used... the rest will consist of the mass of the container and acceleration bucket. This mass will be tossed aside so will not be able to aid in our acceleration.

Using the amount of reaction mass needed to get to 300kps and the packet efficiency I calculated the number of 20kg packets would need to be launched to accelerate our ship. Finally, to calculate the deceleration mass I took the 1500mt m_1 mass after it was done accelerating to 300kps and used a mass ratio of 20 so that our rocket would have enough mass to decelerate at the target star. Along with the reaction mass, I assume that the additional reactor fuel will arrive, after the acceleration phase is done. I also use the same packet efficiency to calculate the number of packets needed.

Some quick conclusions can be drawn. Since the Electric thrust Starship engine mass is so much less the electric thrust version has a far smaller m_1 initially. However, as the thrust requirements go up, the increasing mass of the engines and the power supply make the electric thruster starship mass grow proportionally faster than the Mass Driver version. Also, the electric thruster is slightly less efficient than the mass driver in converting the mass to forward thrust- about 75% of the mass drivers- the directional vector of the electrical thruster's mass is not as directional as the mass driver which sends the entire payload in the appropriate direction. Also, some power is used to ionize the reactions mass. But the biggest impact is that the Mass Driver version uses the complete 20kg packet for reaction mass whereas the electric thrusters would use 50% or less.

It is reasonable to assume that if we make the payload larger, then the mass driver becomes progressively more competitive since the engine mass does not increase and becomes proportionally less and less of the m_1 . To test this out I reran the table with a 100,000mt m_1 payload.

Propulsion Type	Electric Thrusters				Mass Driver			
Thrust (nt)	100	100	1,000	10,000	100	100	1,000	10,000
Specific Impulse (sec)	6,000	10,000	10,000	10,000	6,000	10,000	10,000	10,000
Ve	60,000	100,000	100,000	100,000	60,000	100,000	100,000	100,000
Power (mW)	5	9	85	853	4	6	64	640
Spacecraft Payload	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Engine Mass	133	213	2,133	21,333	13,500	25,000	25,000	25,000
Power Supply Mass	267	427	4,267	42,667	200	320	3,200	32,000
Power Supply Refuel (10000 year mission)	1,227	1,963	19,627	196,267	920	1,472	14,720	147,200
m_1 light (mt)	100,400	100,640	106,400	164,000	113,700	125,320	128,200	157,000
m_1 with Fuel Rplacements (mt)	101,627	102,603	126,027	360,267	114,620	126,792	142,920	304,200
m_2 (mt)	15,040,747	2,052,053	2,520,533	7,205,333	16,963,760	2,535,840	2,858,400	6,084,000
Fuel Flow (kg/sec)	0.0017	0.0010	0.0100	0.1000	0.0017	0.0010	0.0100	0.1000
Fuel Flow daily (80% efficient for electric)	180	108	1,080	10,800	144	86	864	8,640
Acceleration	9.96E-07	9.94E-07	9.40E-06	6.10E-05	8.80E-07	7.98E-07	7.80E-06	6.37E-05
Seconds of Acceleration to 300kps	2.610E+11	2.617E+11	2.766E+10	4.264E+09	2.956E+11	3.258E+11	3.333E+10	4.082E+09
Years of Acceleration (300kps)	8,278	8,297	877	135	9,374	10,332	1,057	129
Reaction Mass	543,833,333	327,080,000	345,800,000	533,000,000	492,700,000	325,832,000	333,320,000	408,200,000
Packet efficiency	50.00%	50.00%	50.00%	50.00%	100.00%	100.00%	100.00%	100.00%
Number of Packets (acceleration)	54,383,333	32,708,000	34,580,000	53,300,000	24,635,000	16,291,600	16,666,000	20,410,000
Number of Packets for deceleration	1,504,074,667	205,205,333	252,053,333	720,533,333	848,188,000	126,792,000	142,920,000	304,200,000
Total Packets	1,558,458,000	237,913,333	286,633,333	773,833,333	872,823,000	143,083,600	159,586,000	324,610,000

TABLE 11-3 PERFORMANCE COMPARISONS WITH 100,000MT PAYLOAD

The mass drivers advantage continues to grow with the higher thrust and as the payload size increases. Once we get to 100,000mt for our payload, our MD becomes the clear thruster of choice.

Mega Mass Driver (MMD)

How do we launch the millions of packets that may be intercepted decades later and hundreds of billions of kilometers away? On our ship, the mass driver has a substantial mass which makes our starship very large. However, mass is not important for the MMD - we will be firmly anchored to a large asteroid. This mass driver could be powered by massive solar panels or large nuclear reactors on the asteroid. Since the weight of the mass driver is now not critical a large and heavy mass driver could be built. Because of this we may be able to relax our 10,000g requirement. Offsetting this is the fact that our starship exhaust velocity was on the order of 100kps and our MMD target velocity is 3x faster. Our MMD would have the following capabilities:

Launch mass: 20kg consisting of bucket and payload (nominal 10kg bucket and 10kg payload)

Variable Velocity: TBD (but may need to vary from 50kps to 300kps)

Acceleration to 300kps: 10,000 g will require a MMD of 441.5km

5000g will require a MMD of 882.9km

While 10,000 g is aggressive the already extreme length of the MMD becomes even more intimidating at 5000g. Some earlier discussions on mass drivers indicated that far higher accelerations should be possible- perhaps 100,000 to 250,000g (Kolm, Fine, Williams, & Mongeau, 1980) but the size of the mass

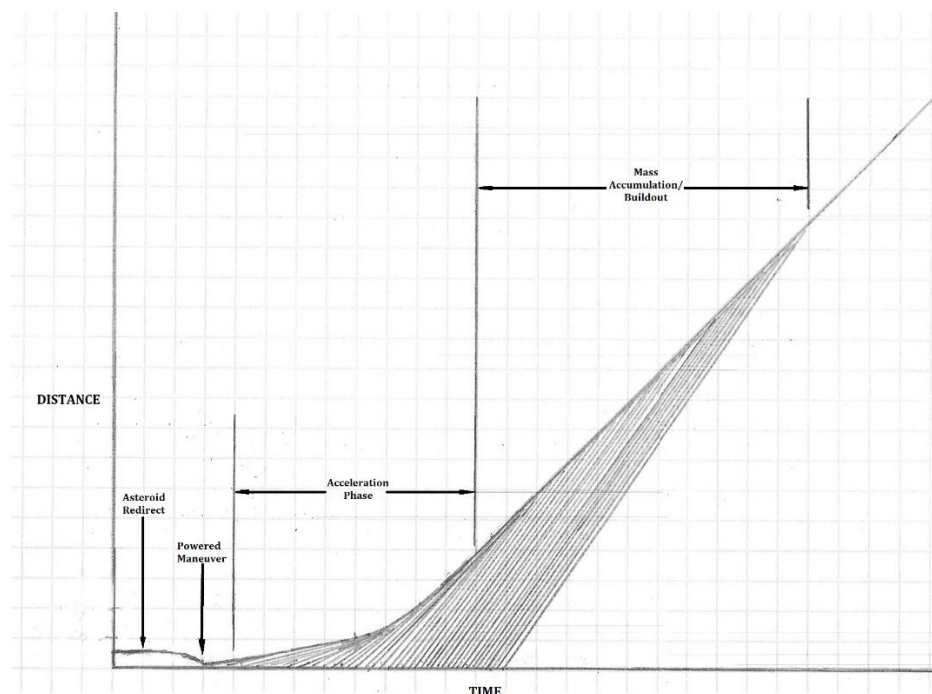


FIGURE 11-2 REFUEL ENROUTE- TIME VS DISTANCE PLOT OF STARSHIP AND PACKETS

being launched is not clear. Regardless, for any reasonable acceleration, the mass driver will be quite long but is essentially an industrial or manufacturing challenge... building a high-power deep space structure 450km long is not an industrial capability that currently exists. We have an additional challenge- the number of packets that need to be sent and how fast they need to be launched. Let us assume that our packets arrive a 1/10,000th of our ship velocity. If our ship velocity is 300kps, our packets will arrive at .03kps (30mps). This means our mass driver needs to send these packets out at 300.03kps. Let us assume the packets arrive at the ship

every 2000 seconds (for a total mass of 864kg per day). Our MMD will have to launch one packet every .2 seconds to be able to achieve this receiving rate at the ship (or 5 per second). The individual packets launched every .2 seconds at 300kps will be spaced 60km apart. At the beginning of the voyage, when the ship is traveling much slower, this is not as big of a problem. If our ship is traveling at 50kps our packets will only be launched every 1.2 seconds. Note that in chapter 13 when we start finalizing our design, it turns out we will need even more power since we will launch 95 packets per second.

Figure 11-2 shows the relationship between our vessel and the MMD and the trajectories of individual packets. It shows graphically the fact that the packets are only traveling slightly faster than our ship. In reality the slope of the graph would be very flat.

This is a serious but not insurmountable engineering challenge. My initial thought is that you would have a gatling gun arrangement whereby you have 3-5 MMD arranged in a circle. How much would this arrangement weigh? I think it is safe to assume that our mass being launched is 20 times more than our starship MD, our device will need to be much beefier. Perhaps we would have ten arranged in a gatling gun configuration linear mass of about 10000kg/meter. On a 441.5 km device this would imply a mass of 4.415 billion kg or 4.415 million MT. This is equal to about 13 empire state buildings (331.1 million mt) (The Empire State Building, n.d.) .

MMD Power Supply

In addition to its large physical size, the MMD will need a lot of power- around 294 GW per projectile assuming 100% electric to kinetic energy efficiency. With 80% efficiency we need about 370GW per projectile. If we need to launch five packets every second we will require about 1,850GW. This is quite large... the United States uses about 3700GW of power so this would be about 50% of the total power usage of the United States. And this launch rate and power requirement is only for our starship recovering 864kg per day.

The firing rate and the power required will be calculated after we determine the size of our ship in Chapter 12.

Packets- Design, Targeting and Production

With the low thrust and large mass of our starship, the electric thruster or MD methods of propulsion on their own do not develop enough thrust to exit the sun's gravitational well. We get around this with a two-stage configuration- the rocket would already be traveling on a hyperbolic trajectory of perhaps 80kps after performing a powered solar maneuver (as with the Saturn VIIC) and then we would go to this propulsion system (either electric thrusters or MD).

The relatively small starship (exact mass to be calculated in Chapter 12) can be launched toward Jupiter. Using the planet's gravitational field along with a small Oberth maneuver of 1 or 2kps will slingshot around Jupiter anti-clockwise and drop toward the sun. As described in Chapter 8, we do a powered maneuver of around 10 kps at the sun. It is only then, when we are on our way comfortably over the solar system escape velocity that we start intercepting our packets and using them to build up our velocity.

Can the packets be accurately projected so that they arrive exactly where they are supposed to? This is a challenge that I believe can be overcome. I conceive of each 20kg packet as a small spacecraft with limited automation. The spacecraft will have a small storage payload capacity of 10kg, the other 10kg would be the container (also the bucket), electronics and sensors, solar panels and a couple of small ion engines. This would essentially be a micro spacecraft that would have sensors to determine accurately its position relative to other packets, as well as the ability to do small velocity adjustments with its ion engines.

Launching our packet with 1/10,000 velocity part accuracy should be doable. At 300kps this means that we can launch with .03 kps, or 30 mps accuracy. For fine final adjustment our packet spacecraft will need to have the ability to adjust its velocity by 30mps. The key is that it will have to adjust their speed to extreme accuracy with the packet in front of it- and follow it with an accuracy of a few cm per year on all three axes'. In the days immediately following its launch the packet spacecraft will deploy small solar panels and get irradiated by laser light that will power its electronics and small ion thrusters. It would actively locate the packet in front of it and with small thrust from its ion engines lock in behind the proceeding packet- with the requirement for an accuracy drift of a few cm per year. I foresee this as happening both immediately after launch for a couple of days or so and perhaps a month later with a separate power station and laser transmitter about another 30-40 million kilometers along the path of the packets to reactivate the packet spacecraft for final fine course adjustment. Note that at 300kps the packets will be traveling at about 1million kilometers per day so our window for fine adjustment will be short.

If we assume the packets will be illuminated by a laser for two days so as to get power to adjust their velocity. This works out to 172,800 seconds. A typical small ion or plasma thruster, like the Hall Effect thruster PPS-1350 needs 1500 watts provides 90mN of thrust- or .09nt. Calculating its acceleration:

$$a = \frac{F}{m} = \frac{.09}{20} = .0045mps$$

To achieve 30fps this thruster would only have to fire for 6667seconds- or about 111 minutes. This is too large of a thruster since it requires 1500 watts with the ion engine massing 5.3kg as well as the fact that we need to get to one packet trailing another packet to within a couple of cm a year drift and a large thruster like this will have trouble with such fine adjustments. We would likely use a thruster only 1/25th as powerful and require only 60w of power. Besides a small solar panel and a couple of ion thrusters,

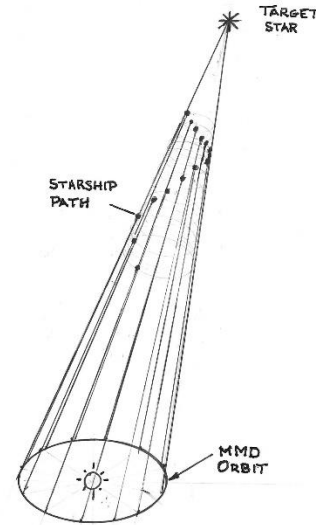


FIGURE 11-3 NOTIONAL STARSHIP FLIGHT PROFILE AND MMD PACKET TRAJECTORY

the packets equipment will include a range finder to find, lock on and track the packet in front of it. Speed and alignment adjustments would then occur over a period of a couple of days.

Even though the individual packets will need only about 60w off power, the total amount of power being beamed will be substantial. We will see that based on the mass of the packets, and our desired rate of acceleration and starship needs to receive a packet every 105 seconds (see Chapter 13). Assuming the packets approach the starship at the rate of 30mps, the MMD, when our starship is approaching 300kps, will have to launch packets at the rate of 95 per second. If we illuminate the packets with a laser for two days after launch this means that at any one time we will have 16.4 million packets being illuminated. Assuming that we have solar panels of 50% conversion efficiency, and that we have a laser that is 50% efficient, and that our millions of swarmed packets only intercept 10% of the light, we will need about 39.4GW_e of power. This is a large amount of power and would likely be split up among multiple lasers, each illuminating only a portion of the packet path.

To summarize our packet challenges would be:

- Launching millions of packets up to a very high speed- ranging up to 300kps
- Launching them at the rate of up to 95 per second (see chapter 13)
- Launching them so that their speed is within .01% of target speed (30mps)
- Beaming power to the individual packets for up to a week to power them and allow them to accurately position themselves.
- Instrumenting the packets, including having small solar panels and small ion engines that will allow them three axis adjustments up to 30mps over the course of the week they are powered. This packet will only mass 10kg and include the accelerating coils.
- Adjusting their speed and trajectory so precise that they will drift from their position by less than a meter per year.
- Mass production of millions of packets. In the everyday world, very complicated devices are frequently produced in huge quantities- witness automobiles, or perhaps more relevant, iPads. The money is spent on designing the first item and building the factory- which frequently costs many billions. After the design is worked out and the production system in place, the actual production costs are relatively low. Sounds easy!

A major concern and serious engineering challenge is building the 10kg empty packet. Unfortunately, with the aggressive goal of a 10,000g acceleration the packet which also consists of the acceleration bucket alone may mass more than 10kg. In chapter 16 we will identify in more detail the payload that will need to be delivered and see that it may be possible to have a considerably smaller payload- closer to 5kg, which will open up the possibility of a 15kg bucket/package and 5kg payload. One option that we may have to consider is that the bucket is decelerated and is recycled back after the payload is released. This may become necessary if the goal of a 10-15kg bucket/package combination proves to be too ambitious. The major disadvantage to this is the requirement to double the length of our mass driver as we will now have to slow the bucket down.

Finally, for no particular reason I selected the total mass of each packet to be 20kg. It may turn out to be desirable or more practical to have a packet 40kg which will half the number of packets launched and permit a larger bucket/package and payload.

Mass produced Solar Sails

The second alternative to the MMD would be a small Solar Sail spacecraft of a similar size to the packets- 20 kg- half of which is payload and half of which is sail. The tremendous advantage is that you need to build no large MMD. Using a trajectory similar to that shown in Figure 9.6 we could send millions of small solar sails on their trajectory. Furthermore, because they will be receiving a continuous, albeit diminishing thrust from the sun, their speed and trajectory can continuously be tweaked over a prolonged period of time in order to set a very precise trajectory.

Building enroute

One difficulty that we still have not addressed is the difficulty of a low thrust, large mass Starship has in leaving the Sun's gravitational well. Because of this we will still have to give our spacecraft an initial push to get it on an escape trajectory. Furthermore, because of the large size that we are looking at, we will start considering the Starship to be constructed in space using resources from the asteroid belt. We will therefore have an initial escape velocity for our starship before the MD starts operating.

Even though this concept of sending out both reaction mass and supplies via an MMD adds complexity it effectively removes a lot of problems by not having our starship carrying all its reaction mass for decelerating as well as being able to deliver replacement Uranium fuel. To summarize our new mission would look like this:

- Because of the low thrust of our MD which would make it difficult to escape the sun's gravity, we will assume an initial velocity of 40kps for our ship.
- A target velocity of 300kps. Our MD will provide a 260kps acceleration. Table 11-2 and 11-3 assumed 300kps provided by the MD.
- A thrust (average) of 10000nt.
- Assume a m1 of 100,000mt.
- To get our 260kps with a 10000nt engine, we will need about 129 years of acceleration.
- Since our starship needs to decelerate using stored reaction mass, if we use the 20:1 mass ratio we will need increase our starship final cruise mass to 2 million mt.
- Resupply would occur for part of the mission including replacement of volatiles and other materials expended. This includes Uranium. This can effectively eliminate the need for carrying large amounts of enriched uranium at the start of the mission.
- Because the starship will be supplied after the initial acceleration phase, it can also be expanded and assembled during its journey. This will further reduce our starting mass. We shall see in the next chapter that our cosmic ray shielding will be even more massive than our engines. This mass can now be added as the voyage progresses.
- The assembly of the rocket and colonizing ships will keep the crew busy during the 10,000-year journey. One concern that will come up later is what will a crew do during the voyage. Part of this answer is to build and expand the ship.
- Build our supplies and capabilities for planetary exploration and colonization.

Refining the mass and velocity profile originally showing in Figure 10-2 the new mission profile would look something like

Figure 11-4. I see the mission as starting with a small colonizing craft from Earth that would land on a small, ice/water rich asteroid. During the next few years, the colonists would build out a more permanent colony while they would also create fuel (either hydrogen for a Nuclear Thermal or LH/LOX for chemical engine- we will determine which is better later). The asteroid would have a large Δv applied, probably over several months that would remove most of its

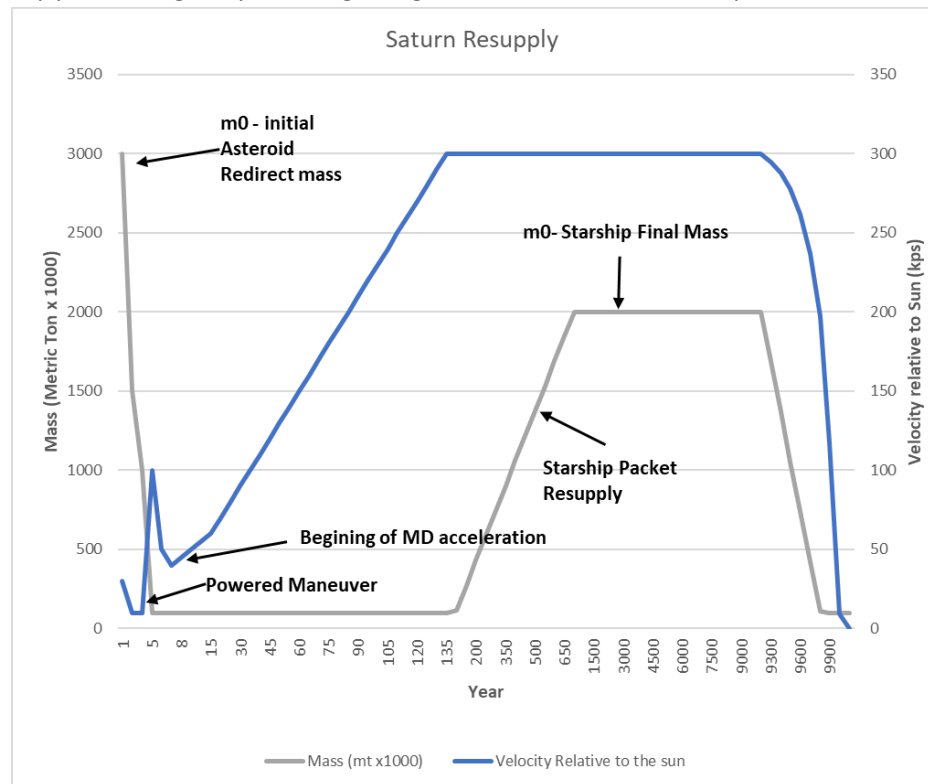


FIGURE 11-4 NOTIONAL MISSION MASS AND VELOCITY PROFILE

forward momentum so that it would drop down toward the sun. At the sun we would perform a powered maneuver. The starship would now be traveling at a substantial escape velocity. Within a short time (couple of months to a year or two) packets would start arriving and the starship would begin accelerating with its low thrust but high-performance MMD engines. After this acceleration phase is complete, we continue to receive mass, but this is now used to build up our reaction mass needed for our 20MR on deceleration. After coasting for several thousand years we will fire up the starship's mass driver and consume all this material and bring us down to a $m_{1\text{arrival}}$ mass. As with Figure 10-4 the numbers in Figure 11-4 are representative- we still need to calculate the $m_{1\text{outbound}}$ of our ship.

Note that our final $m_{1\text{arrival}}$ mass at our destination star, which I will call $m_{1\text{arrival}}$, may be different than the original $m_{1\text{outbound}}$ mass. The outbound crew knew that after the initial acceleration they would continue to receive supplies. The ship on arrival will not have this luxury and may have a slightly larger mass to include colonizing supplies.

The remaining open issues will be determined once we figure out how big our Starship has to be. In Chapter 12 we will define this and settle on a minimal mass. By determining the $m_{1\text{outbound}}$ size we can determine the size of our power plants, our engine selection, our overall capabilities and finally our m_0 .

Determining our size and nature of our mission will determine the resupply requirements- what materials will we need? Some items we need to consider what are the required quantities of:

- Water. To act as a cosmic ray shield and to replace lost water or through electrolysis break down to get oxygen lost during the voyage.
- Fuel- ^{235}U to replace our depleted uranium
- Nitrogen. This is one element that is not easy to replace. Being a gas, it will slowly leak out over time. It could be replaced either by keeping a supply of liquid nitrogen or, more likely, ammonia.
- Metals like Aluminum, Nickel. You will likely need to have additional metals for building your landing ships as well as expanding your habitable space.
- Carbon, Phosphorus, and other life critical elements. Needed for healthy plant growth but the amounts needed are very small and could be brought on board from the start.
- Other volatiles and miscellaneous

Also, in Table 11-2 and 11-3 we came up with the rough number of packets needed. These were just placeholders. Until we determine our $m_{1\text{outbound}}$ we cannot calculate an accurate total mass and therefore determine the number of packets, our propulsion options, how fast our outbound acceleration will take, etc.

Summary and Conclusions

In this chapter we have come up with a possible mission profile. In the next chapter we will develop the specifics of our Saturn C. The mission will have the following targets:

Target Speed: 300kps (10,000-year voyage)

Refueling enroute (to reduce our starting and total mass)

Resupply enroute (to reduce our starting and total mass)

Isp of 10,000sec (to reduce our total reaction mass)

Power Supply generates 20W/kg; extra uranium will be provided for by enroute resupply.

While there are many challenges of this approach, this scheme looks achievable with several caveats:

- Can we get these fuel and mass packets up to 300kps?
- How do we keep the packets at the proper trajectory and speed to be picked up by the starship?
- Will we be able to launch the packets quickly enough? What will be the required rate?
- Will it be practical to make possibly millions of packets? How many packets will we need?

There are several things that we can look at and adjust. For starters:

- If we desire our ship to have a higher thrust, we can increase the mass flow.
- Have the ship approach the packets at a faster speed. Suppose instead of approaching at 30 mps we approached at 1 kps. This would reduce the rate the packets needed to be launched, as well as the time the packets will be in transit.
- Increase the mass of the individual packets so that you need fewer packets. A 100kg packet mass would reduce the number of packets you needed to $1/5^{\text{th}}$.

- Build multiple launchers in gatling gun like fashion. This will permit redundancies and permit one or two launchers to be down for repairs.

An alternative to the MMD would be small solar sails. With a Solar Sail we would target a 10kg payload. If we assume a solar sail mass of about 10kg we have a 20 kg spacecraft. To achieve a velocity of 300kps and assuming a sail loading with perfect reflectivity of 1.53g/m^2 , we would need to open our sail at a blistering 2million km from the center of the sun. The size of the sail for a 20 kg spacecraft would be 30600 m^2 or a square sail 175m on a side. The heating for even a highly reflective sail would be substantial and may not be survivable. However, if we could reduce the weight to below the sail loading of 1.53g/m^2 we could launch these sails farther from the sun. The advantages to using solar sails is tremendous- it would totally eliminate the MMD. Furthermore, their speed can be finely adjusted as they accelerate away from the sun. The problem is whether it will be possible to build a sail with the required sail loading factor and able to survive the high temperatures.

In the next chapter we will focus on what our m_1 mass is. Once we determine this, we will be able to calculate many of the unknowns- how many packets we will need for acceleration, how frequently the packets will need to arrive, how powerful our reactors need to be, how fast we will accelerate, and how large our m_0 will be.

Chapter 12- Saturn C- 2090's

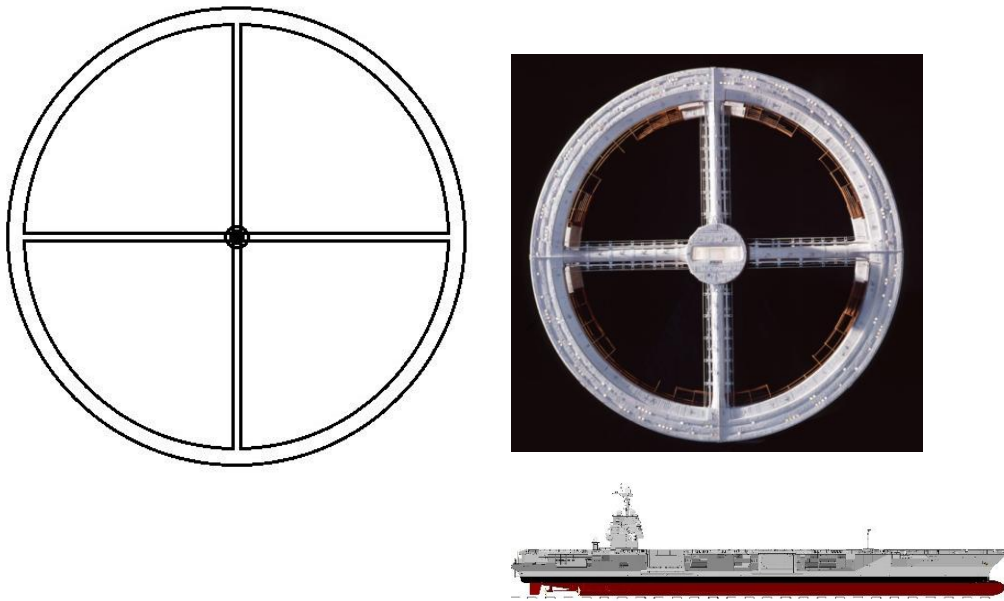


FIGURE 12-1 SATURN C TORI PROFILE, SPACE STATION V (FROM 2001), AND FORD CLASS CARRIER (TO SCALE)

Beginning with Chapter 10 we relaxed our starship size. The Saturn XA ion engine drive was an effective design but hampered by a huge mass ratio necessitated by the need to decelerate at the target system. This huge mass also severely limited its acceleration and overall performance. With the Saturn XC, we fundamentally changed the mission architecture, whereby we refueled enroute. This seems a more reasonable and practical path, but in our first cut we developed the mission outline but really did not consider how large the empty spacecraft baseline mass really needs to be- though the requirements for power, the long mission, and in the case of using a mass driver for thrust, would be far more than our 1500 mt Saturn X and likely larger than the 100,000mt we considered in Chapter 11.

In this chapter we will set the following goals:

- The starship will have to have a viable crew size to travel for many thousands of years and colonize a star system on arrival.
- Starship will have a target speed of 300kps. This will lead to a 10,000year voyage.
- Starship will need to slow down at the destination.
- Starship will pick up reaction mass on outbound portion of journey for acceleration and, after acceleration, for reaction mass to for both resupply and to decelerate at the destination.
- Starship will use onboard deceleration mass to stop using a mass ration of 20:1
- To stop from our 300 kps approach velocity and 20:1 mass ratio we will need to have an exhaust velocity of 100 kps. Our Isp will therefore be 10,000sec
- We will have advanced fission reactors that generate 20W per kg.
- We will assume that some level of Uranium re-processing is done sufficient to reduce the required Uranium by 50%.

- Relatively high thrust. As we saw in Chapter 10, thrust will need to be relatively high to be able to accelerate a large vessel. We do not want to spend several thousand years accelerating- our packets will drift and after several thousand years, are unlikely to be able to be retrieved. Furthermore, as we shall see, Cosmic Radiation will be an issue during the acceleration phase- but more on that later.
- We will look at alternate propulsion systems but realistically only Electric propulsion like Ion/Plasma thrusters or Mass Drivers can provide the thrust and Isp we will need.

Let's start providing some definitive answers to achieve our goals.

Saturn C

Before this configuration we looked at unmanned ships for the simple fact that the vessels were small and built in earth orbit from earth supplied materials. However, this is inadequate since our velocity limitations are driving 10,000-year mission. A crewed mission is the only one able to conduct the extensive repairs and modifications that would be necessary over the centuries of travel. An automated mission that lasts for 10,000 years would even be more technologically challenging and difficult than a crewed one. Furthermore, a crewed mission would energize both the mission preparation as well as the voyage far more than an automated probe.

This is going to be a one-way mission to colonize a world. Because of this we need to consider the minimum number of people needed. The vessels primary components will be:

- Habitat
- Power supply
- Colonizing materials for arrival at the target solar system (landing craft, supplies etc.)
- Engine

Before we can figure out these component masses, we need to determine how large our habitat will need to be.

Habitat

There have been several designs that have been considered for large size multigenerational space stations or so-called world ships. When designing the habitat we need to consider:

- How many people does the habitat need to support?
- What are the artificial Gravity requirements?
- How much space or volume do we need for the spaceship for sufficient individual needs?
- What is the atmospheric pressure we need to maintain for our spacecraft?
- How much area is needed to grow crops/food as well as to live? What are the food requirements for the colonists? How much land will they need?
- What will we make the spaceship out of?
- How much power will we need?

We need to look at all these areas and make decisions before we can develop an estimate for its mass. In later chapters we will discuss the power supply and the actual operations of the Starship including how our resources will be recycled.

One of the basic questions before we can even start addressing these issues is determining what is the shape of our starship?

NASA looked at this problem as part of a 1975 study that was consolidated and published in 1977 (Johnson & Holbrow, 1977).

In this study, the goal was to build a habitation for 10,000. Their design assumed a 1 rpm rotation rate. The single torus was determined to be the best design, requiring, on balance, the least structural, cosmic ray shielding and atmospheric mass. They called this station the Stanford Torus.

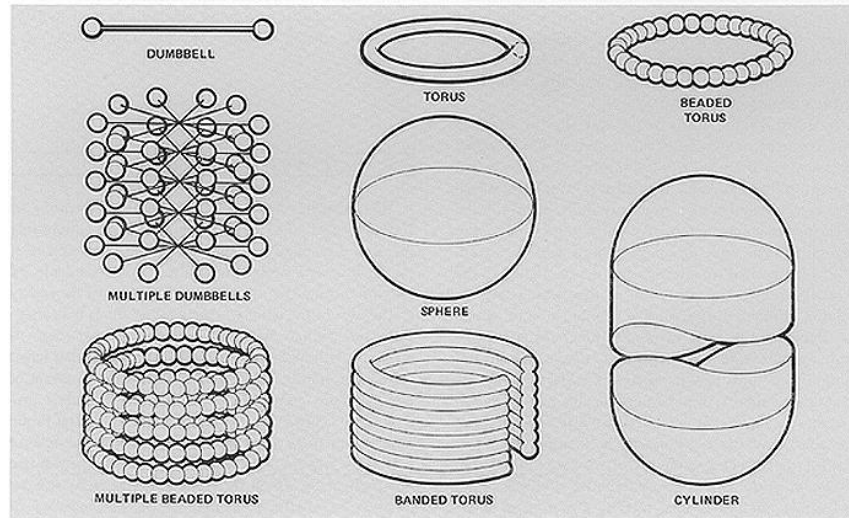


Figure 4-2.— Basic and composite shapes.

FIGURE 12-2 (JOHNSON & HOLBROW, 1977, P. 41)

The 1975 study addressed many of the same issues that we will be looking at though their goal was considerably different. A majority of the study considered the design and construction details of building a large space station orbiting at the L5 point. As such, their design emphasis is considerably different than ours... they were looking at larger population, abundant solar energy for power, an unmoving station in stable orbit and a space construction location relatively near the earth (at the L5 point). Most of the raw materials that were needed were provided by the moon. The primary end results of this were a station much larger and heavier than we will be considering. Since it was not designed to be interstellar travel but instead was to be in an L5 orbit, it took advantage of solar energy for illumination and power. Their Stanford Torus had the following parameters:

Population	10,000
Major Radius (R_{Major})	895m
Minor Radius (r_{Minor})	65m
Gravity	1g
Rotation Rate	1rpm
Atmospheric Pressure	½ Sea Level (500mbar)
Structure Material	Aluminum Shell

TABLE 12-1 STANFORD TORUS

Many of the ideas that were laid out in this study can be adopted with appropriate modifications for our starship. As opposed to the Stanford Torus, our starship will be much smaller and need nuclear power.

How many people does the habitat need to support a viable population?

Since we are on a several millennia voyage, with the ultimate goal of colonizing a world, we need to

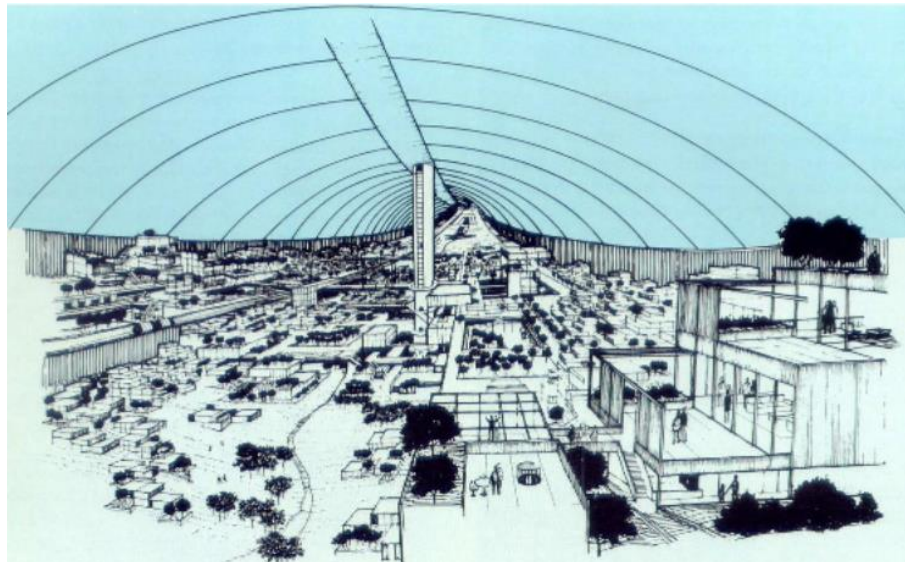


FIGURE 12-3 INSIDE OF THE STANFORD TORUS; NOTE THE LARGE 130M MINOR DIAMETER SHELL (JOHNSON & HOLBROW, 1977, P. 81)

have a population large and genetically diverse enough to survive indefinitely. How large this population needs to be is called the minimum viable population and agreement is surprisingly hard to find in the literature. Opinions vary from as small as 98 (Powell, 2018), or even a single couple, to as many as several thousand (Stenger, 2002) (Yampolskiy, 2018).

In keeping with my desire to make this exploration as realistic as possible, I

originally selected a minimum number of 250. This is squarely in the middle of many estimates. In addition, even though some literature suggest smaller numbers are genetically viable (especially if we add the possibility our bringing along frozen embryo's to further increase the genetic diversity) we need to consider other factors other than pure genetic considerations. Would you want to be on a lifetime voyage with only a few dozen people? One positive is that children will always be being born so there will be a turnover and new faces, but genetic diversity and viable social interactions will dictate something more than the minimum. Furthermore, our intent is to colonize another star system. In both the voyage as well as colonization we could conceive of several disasters that could kill a portion of the crew. Suppose a landing craft blows up while shuttling the colonist's down to a planet's surface? Arriving at a new solar system with 250 people would be challenging to populate- it will take thousands of years to build up the population and the industry of the new star system. In addition, during the long voyage the numbers of colonists will likely vary perhaps by a lot, and over the dozens of generations populations may vary considerably, both below the average and above. For these reasons I have considered a ship that will average 1000- ideally keeping within 750-1250.

For our voyage some issues we will need to consider and address:

- How stable will the population be over time? Will we be able to stay within a couple hundred of our 1000? Suppose over time the population starts creeping up? What will they do? If the voyagers depart when they are fairly young, a baby boom may ensue the first ten years. If instead the voyagers depart and their average age is older- say in their mid to late thirties, then

there may not be enough children on the first few generations to replace the seniors as they die and our population may drop below our minimum.

- Natural variation will play a role but so will cultural norms. Over a long period of time, woman will need to average just over 2 children. If they average only 1.9 the population will decrease rapidly after a few generations. Conversely if they average 2.2 over several generations the population will grow rapidly. What will be the mechanism to ensure the number stays within a reasonable range?
- What happens if there is a disaster that reduces the population substantially during the voyage? At the beginning, frozen embryos may be able to supplement and help with genetic diversity, but it is unlikely that frozen embryos will be viable after a thousand years. A continuous renewed supply of frozen embryos would be prudent.
- Even if technically and genetically it is possible to keep a viable population of 1000 people, will this be enough to maintain a vibrant and healthy culture?

What are the artificial gravity requirements? What will be the radius?

After picking the crew size we need to discuss the artificial gravity requirements next because this drives radius, and hence the size of our habitat. There have been many studies on what gravity requirements are necessary for long term health- but there is no actual data on the effects of lowered gravity. All data collected to date are either from studying organisms at full earth normal gravity or essentially zero gravity from long term missions on various space stations. The only low gravity data that we have is from the Apollo astronauts who spent a few days on the moon in $1/6^{\text{th}}$ gravity. Because of this paucity of data, most studies have drawn uncertain conclusions on what people can tolerate in the long term. From the studies from long term Space Station experiments it is known that there are serious effects of no gravity, some effects transient and some permanent. In general, the consensus is that people cannot remain healthy in a zero g environment for extensive periods over a year or two. The question still to be answered is for a multigenerational starship, what are the minimal gravity requirements that are required to prevent these long-term problems?

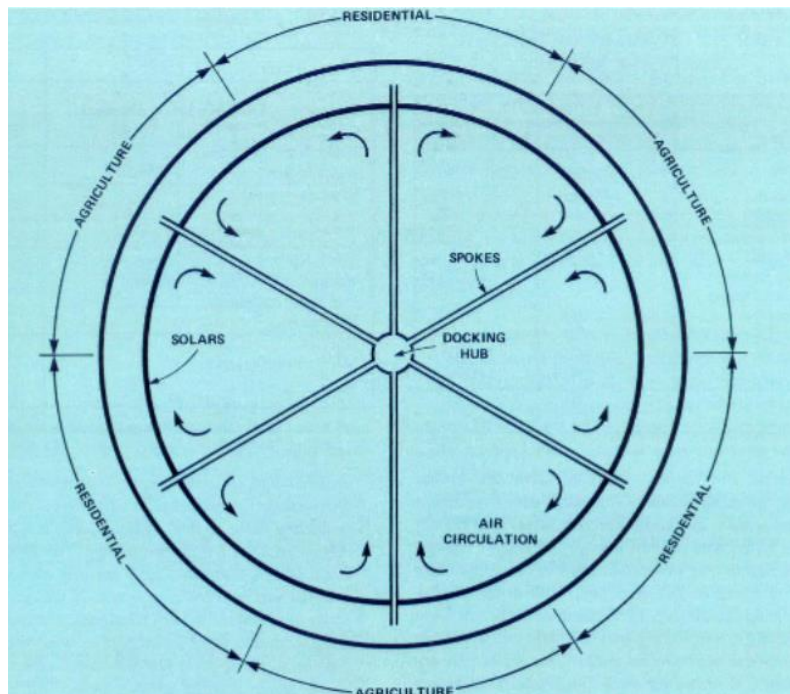


FIGURE 12-4 STANFORD TORUS LAYOUT (JOHNSON & HOLBROW, 1977, P. 86)

Fortunately, artificial gravity is easily created via centrifugal force. An object, being spun around in a cylinder will feel a gravitational acceleration per equation 4-1. Putting this term into equation 2-2 we get:

EQUATION 12-1 $F_c = ma_c = \frac{mv^2}{r}$

Force will increase as the square of the tangential velocity divided by the radius. To develop an optimum solution to long term habitation we need to specify two items- what is the gravity we need to minimize health effects, and how fast can we spin without causing excessive discomfort to the colonists?

The first question is to determine what is the minimum amount of gravity the colonists can function in indefinitely without health effects? The easiest answer of course is what we experience every day on earth- 1g. We know that humans have evolved in 1g so that would be the natural choice. Even though it is known that there are severe negative effects of zero gravity, it is likely that humans, being fairly flexible creatures, could live their whole life in a lower gravity with no ill effects. We just don't know what that limit could be.

A couple of disadvantages of having a 1g gravity vs a lesser amount is the size and strength of the habitat. Higher gravity requires a structurally stronger (and heavier) spacecraft as well as requiring a larger diameter for a given spin rate. How does the rate of spin affect the diameter?

For a given centripetal gravity we can calculate the required radius by determining the rotation rate required to give us 1g acceleration.

EQUATION 12-2 $v = \omega r$

Where ω = *angular velocity rad/s* and is equal to:

EQUATION 12-3 $\omega = \frac{2\pi}{T}$

Where T = *orbital period measured in seconds*

Substituting into equation 12-1

EQUATION 12-4 $a_c = \frac{(\omega r)^2}{r} = r\left(\frac{2\pi}{T}\right)^2$

Substituting into equation 12-2

EQUATION 12-5 $F_c = mr\left(\frac{2\pi}{T}\right)^2$

Rearranging Equation 12-5 we get the following for r:

EQUATION 12-6 $r = a_c\left(\frac{T}{2\pi}\right)^2$

Using an arbitrary T of 1 rpm the following are some Diameters.

Gravity	Radius (1 rpm)	Radius (2 rpm)
1 g	894 meters	224 meters
.9g	802 meters	201 meters
.5g	447 meters	112 meters

TABLE 12-2 GRAVITY VS RADIUS FOR 1 AND 2 RPM

In theory, if you have a small radius, you can still have one gravity of force if you spin very rapidly. However extensive studies as well as real life experiences show that people don't adapt well to being spun fast-and these various physiological effects become more pronounced as you increase your rpm. The main effects are:

- Centrifugal force varies with distance from the center. If you have a small diameter radius and rotate rapidly the gravity at your feet will be higher than your head. Standing up or sitting down will cause substantial variations in what your body feels.
- Coriolis effect is particularly unpleasant- its effects are on the inner ear which can cause dizziness, nausea and disorientation. If you move towards the axis of rotation, you will feel a force pushing you either towards or away from the direction of spin (depending on whether you are heading toward or away from the axis of rotation).

The Stanford Torus picked the conservative value of 1 rpm. Before the selection of the Stanford Torus, the original design was for an O'Neill cylinder that rotated at 3 rpm. The concept of this space habitat was that many of the colonists would be working on projects in zero g and then return to their homes every day. It was felt that in this case going back and forth between the two environments the Coriolis effects would cause motion sickness (Heppenheimer, 1977, p. 114). The design team decided that this spin rate was too aggressive and that a slower spin rate would make the O'Neill cylinder too large. Because of this, when the team went to 1rpm they switched to the Stanford torus. One of the studies team members, Wink Winkler felt very strongly that the proper rotation rate should be 1rpm or slower (Heppenheimer, 1977, pp. 115-116).

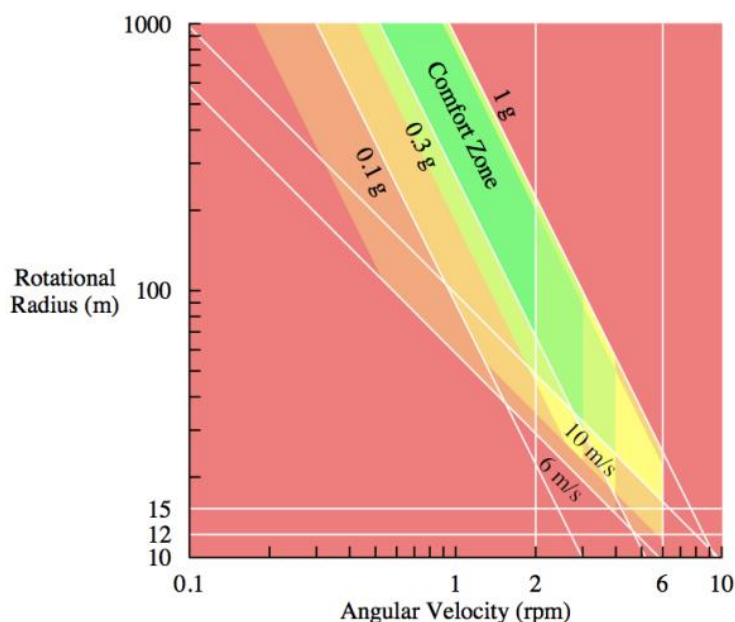


FIGURE 12-5 (GLOBUS, SPACE SETTLEMENT POPULATION ROTATION TOLERANCE, 2017)

Despite the Settlement Design teams thoughts, most of the literature indicates that people can adapt to a rotation rate faster than 1rpm with no motion sickness experienced- especially, as in our starship, they will be staying within the torus ring and not frequenting the low gravity hub. A summation of literature indicates ranges from one to six rpm might be acceptable (**Figure 12-4**). Most studies indicate that 2rpm is probably the highest you would want to go. Let us pick 2 rpm as the upper limit for our calculations. Even though we have not picked the internal volume of the spacecraft, we know it will not be small like the international space station. People are going to want to move around, exercise, play sports etc. Assuming 2 rpm Table 2-2 shows the considerably smaller diameters that would be required.

It always has surprised me as to how large these Radius (and hence) diameters are. How low of a g force can we go before we have serious effects on human physiology? It is impossible to say. Once we have established extensive colonies on the Moon (gravity 16.54% of Earths), and Mars (37.94% of Earths) we will get a better idea. If we are very conservative, we may use the 2rpm figure at 1 g, but we may be able to go to .75g or even .5g (or even lower) but we don't know. Because we want to save mass but have no data to support what the number should be, I am being slightly aggressive but will establish the habitat target of .9g, 2rpm with a radius of 201 meters. With our diameter now 402 meters its circumference would be 1263 meters- or about one and a quarter kilometer.

What would the volume be of the habitable portion of the ship?

With our key decisions of having a ship with .9g gravity, and a nominal population of 1000 we can start designing some of the general parameters and requirements for our vessel. Two of the first things that must be accounted for in determining the ability to support this many people are- how much space is

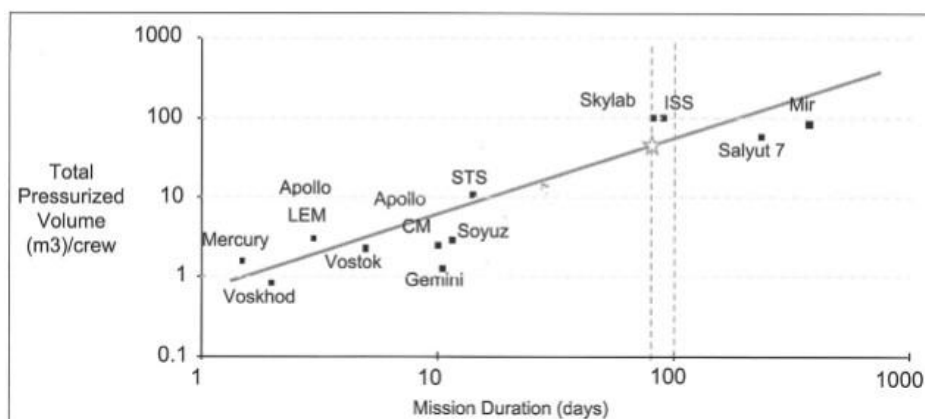


FIGURE 12-6 PRESSURIZED VOLUME VS MISSION DURATION

required for people, how much land is needed for food and relatedly, how much power would be needed to grow sufficient food to support 1000 personnel? In addition, to calculate the mass of our ship we need to select the material we will make the ship out of and how thick our metal would be.

While it is difficult to extrapolate from our current small spacecraft, the general trend is that as missions grow longer and crews larger the space per person grows. There is no science to this- but it is obvious that a person will tolerate much closer existence during a mission of a few days vs a lifetime.

Besides the historical trends in space, we also have a history of many men and woman working together in confined space- such as a submarine. For a submarine it is about 12 m³ per man. But submarines are military vessels, with no children, frequently no woman, and only are out to sea for a few months. The ISS has a much more generous 100 m³ per person. This is probably the minimum that we would like to use for a 10,000-year mission- and the graph above seems to suggest a number closer to 500m³/person. However, there is no requirement for this. The conclusion I draw is that assuming 1000 crewmembers, the absolute minimum would be 100,000 m³ or 100 m³ per person.

In addition to the psychological aspects of having enough space for privacy and all-around wellbeing, we will have to grow food. How will this be grown? High density growing methods frequently lead to amazingly high productivity. We need to ask what kind of food will be grown? Will the colonists be living off traditional foodstuffs like meat, fish, eggs, grain? Or will it all be advanced hydroponically and genetically modified plants? Or will they be doing something in-between? Decisions would have to be

made which may drive our design but for now we will assume that our spacecraft will be designed to have enough space to grow crops and livestock of some sort.

During the work done in support of the Space Settlement Design Study, an analysis was performed to see how much land was needed to grow enough food of varied kinds, including various crops, eggs, milk, beef, pork and fish. One conclusion drawn was that only 100 acres were required to feed the colony of 10,000 (Heppenheimer, 1977, p. 128) and perhaps much less. The starship, being totally artificial, can adjust lighting to be 24/7 if desirable. In addition, the atmosphere can be adjusted to have slightly more CO² which aids in plant growth. This question will need to be extensively studied. What food will be grown? Will there be fish? Will there be milk? Where will the milk come from- cows or goats? Will there be meat and where will the meat come from-cows, lambs, chickens, rabbits? The

Stanford torus looked at using goats (more efficient and producing milk than cows) and small, fast growing animals like rabbits and chickens for meat. However, in the intervening half century a lot of progress has been made on “growing” meat without the animals. Genetically Modified Crops (GMOs) have been developed that have drastically reduced starvation and substantially improved crop efficiencies. As compared to the productivity numbers from the mid '70's crop efficiency is likely to be much higher. How advanced with crop, fish, eggs, milk production be in the near future?

For our starship I believe we should be able to double the efficiency over what was proposed in the original Stanford torus which was conceived in the 1970's. If that proves doable, then based on the target of 1000 colonists, we will assume 5 acres of dedicated farming- about 20,235 m². Keeping in mind that we will also need land for housing and manufacturing we can reasonably assume aggressively that 75% of the total land is farming and the remaining 25% for all other purposes we would require a minimum 26,980 m².

Note that our torus would have two levels and crops can be grown on both as per Figure 12-7. As a general rule regardless of the diameter I have always placed the main deck slight below (from 1m to 1.5m below) midline. This is to increase the overhead space to provide a feeling of more spaciousness as well as to give more room to build structures on the sides.

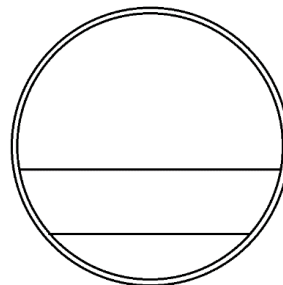


FIGURE 12-7 PROPOSED TYPICAL TORUS BARREL CROSS SECTION WITH 2 DECKS

[What pressure will the spacecraft operate at?](#)

We also will need to determine what the atmospheric pressure within the Torus will be. Sea level pressure is about 1013 kilo Pascals(kPa) or 1013 mbars. Most humans can comfortably live with atmospheric pressures at 80% of sea level- equivalent to a 2000m altitude. This is about what people in Denver Colorado experience. In addition, we can survive at much lower pressures if we increase the ratio of Oxygen to Nitrogen. At sea level, our atmosphere consists of 21% Oxygen, 78% Nitrogen, and about 1% everything else (mostly Argon, but trace amounts of other gasses like Xenon, CO₂, and water vapor). As pressure decreases, we can offset the decreased oxygen available by increasing its ratio

compared to the other gases. As long as oxygen pressure is equivalent to 340mbar (called the partial pressure) then humans can survive. Some spacecraft do this- and carry it to the absolute limit by operating at 340 mbar of pressure with a pure oxygen atmosphere.

The Apollo missions operated at 340 mbars because there are several advantages to having low pressure. For one it saves weight, partly because it eliminates the need to carry (and store) nitrogen. Reducing the pressure on your spacecraft also allows your vessel pressure hull to be lighter- thinner metal walls and less structural reinforcement- though this may not be as big an influence as you might think. The wall thickness of your average spacecraft is rather thin and other items over and above the atmospheric pressure have to be taken into account- including the need to tolerate high accelerations on launch and landings, and punctures from something dropped or hitting a wall. With that being said, the lower pressure does allow for a less robust structure and will save weight. A robust structure becomes more important for larger spacecraft designed to have people in it for years or centuries. The structural loads are substantially more at 1bar vs 340mb- and the wall or shell thickness (as we shall shortly see) becomes much larger.

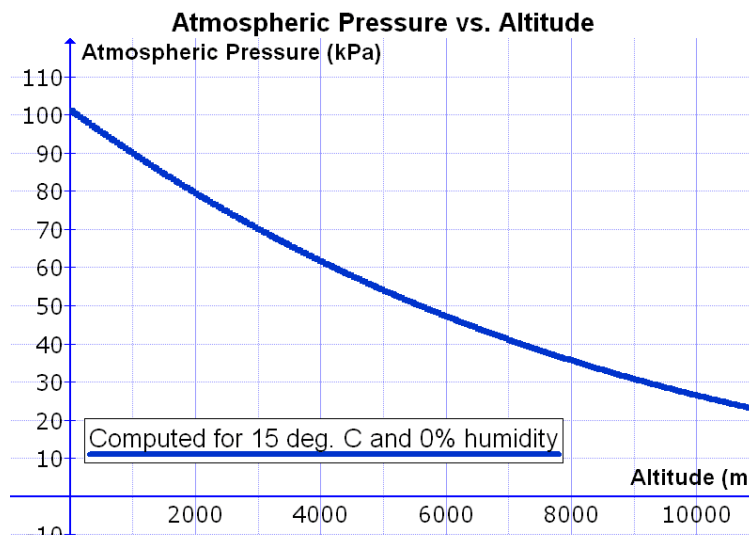


FIGURE 12-8 ATMOSPHERIC PRESSURE VS ALTITUDE

In addition, the mass of the gas becomes much larger on a 1000mbar spacecraft. This does not matter much for a spacecraft that only has a pressurized volume of a few meters but for our spacecraft with 10,000m³ of volume it becomes more of an issue. The density of gas follows closely, but not exactly, the pressure curve. If you have half the atmospheric pressure, your density will be about half.

One of the biggest advantages of the Apollo missions operating at such low pressure is it allows you to quickly get into and out of a spacesuit. If your spacecraft operated in a 1atm atmosphere and you wanted to go out in a standard low-pressure suit, you would have to spend time “decompressing” so as not to get the bends. Spacesuits also operate at low pressure and pure oxygen so that they can be mobile. A high pressure 1atm suit would be very stiff and virtually impossible to move around in- think of the Michelin tire man. With high pressure, the fabric would have to be thicker and stronger to hold the pressure which would make the suit even stiffer and add weight.

In short, a 1atm spacecraft will have to carry more gas (primarily Nitrogen) and will have greater structural stress, possibly necessitating thicker steel /aluminum with greater reinforcement. For this reason, we would like to operate at as low pressure as possible. Nevertheless, there are also disadvantages to operating at low pressure.

One serious problem with low pressure is that in a 100% oxygen environment fires become more dangerous. Pure oxygen is both corrosive and very reactive. Even though the amount of oxygen, the

partial pressure, is the same as in a 340mbar pure oxygen atmosphere as a 1000mbar earth normal atmosphere, the lack of Nitrogen buffer gas means that the fires will burn more intensely and be more difficult to put out. This led to one of the tragedies of the Apollo program when a small fire in the command module during a ground test led to the deaths of three astronauts when the inside of the capsule was consumed by fire and they were unable to open the hatch.

Another negative with low pressure is that sound travels less well in a thin atmosphere. Aboard spacecraft operating at 340 mb, the astronauts had to shout to be heard. A larger spacecraft, where space between the colonists would be more like a normal earth environment, shouting would have to be continuous and exhausting. The same sound problem would exist for alarms and announcements as well as playing music.

Finally, low pressure atmospheres are less comfortable. At low pressure the atmosphere can't carry much moisture and as a result, becomes very dry. Modern commercial aircraft flying at altitude reduce the cabin pressure to reduce the stress on the aircraft skin- but this causes discomfort for the passengers. Many aircraft reduce pressure to the equivalent of 2100m- though some older aircraft went to 2400m. More modern aircraft operate at a higher-pressure equivalent to 1800m since this has been shown to be more comfortable. I believe the Space Settlement Design Study was overly aggressive in picking an atmospheric pressure of only 500mb. This is equivalent to the pressure at 5500m.

For hearing, comfort, and safety reasons I will therefore pick a compromise pressure 80% of sea level. This is slightly less than the average pressure in Denver.

How much "land?"

We have a little bit of a chicken or egg scenario. The size of the ark is dependent on many things, and depending on our decisions, it can affect other parameters and change our conclusions. Some of these parameters are well known but others are not. To give us some boundaries to begin designing our starship, here some of the parameters we have identified, as well as some we still have not:

- How many people will the ark be designed for? We have determined that the population will average about 1000 people and will require a volume of at least 100,000 m³ to ensure sufficient volume for the colonists.
- What is the diameter D of the ark? We have identified 402 meters at 2RPM to provide .9g. This will give us a centerline circumference of 1263 meters.
- What is the atmospheric pressure within the Torus? We have selected 80% of atmospheric pressure for our mission or 80kPa.
- We have determined that we will need about 26,980 m² total which includes 20,234m² (5 acres) of land dedicated to crops and food production, and the balance for living space, manufacturing facilities etc.
- We still need to determine what is the torus barrel diameter and shape of torus including internal arrangements dedicated for living and food production? These answers are partly driven by the next few questions.
- How much power is needed to grow the food (i.e. light) and assorted electrical requirements for the colonists?

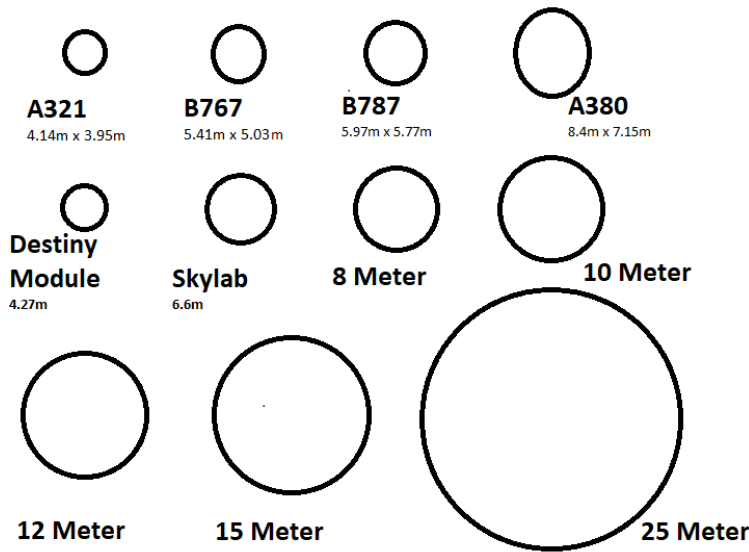


FIGURE 12-9 TORUS CROSS SECTION TO SCALE

Let's look at various r_{minor} dimension. If we have a diameter of the torus at 402 meters in order to maintain an artificial gravity of .9g. What would be a viable living area?

On the International Space station (ISS), the cross sections of the various modules that make up the space station had to be less than the diameter of the SS cargo bay, or 5 meters. In reality, the largest module by habitable volume, the Destiny module is about 4.27 meters in diameter. Note also, that the internal diameter would be even less because of the structure thickness and insulation.

To date, there has been only one larger diameter habitat launched into space. As discussed in Chapter 5, Saturn V launched the orbital workshop Skylab in 1973. Skylab, since it was essentially a modified third stage, had a relatively huge and, to this day, record breaking diameter of 6.6 meters. Figure 12-9 compares some proposed cross sections with those of aircraft.

The largest fuselage barrel that can be currently launched into space is limited by the diameter of the upcoming Space X starship- the outside diameter is 9m but what can be carried inside would more likely be limited to about 8m. If the barrel sections that make up the torus were curved and were lifted up from earth with the Starship, they would have to be smaller than this, as the curved barrel section would have trouble fitting into the straight cargo hold of the starship.

To begin with let's assume that we could launch barrel sections of up to 8m from the earth. How would the interior be arranged, and what would be the internal pressurized volume? With these decisions made we will also be able to get an idea of the surface area and derive the weight of both the structure as well as the atmosphere and other materials that may be needed to fill up the habitat.

Figure 12-7 shows a notional cross section- a double decker arrangement. When calculating the total available surface area, I make the following additional assumptions:

- Assume that our main floor width is slightly less than our barrel diameter to account for a small amount of insulated wall thickness and the fact that the main floor is slightly below the mid line. For simplicity I will always assume the main floor is 1m less than the width D.
- Assume that the second, subfloor deck is 60% of the floor width of the main deck.
- Use the average Circumference when calculating the floor area for both decks.

Suppose we take a small diameter hull of 8meters. Subtracting our 1 meter off the diameter of the hull our main deck would be about 7 meters wide. We have already established that the circumference is about 1263 meters. This means the internal floor area for the main deck would be:

$$A = 2\pi RW = 2\pi(201)7 = 8,841 \text{ m}^2$$

Taking into account the lower deck we would multiply our area by 1.6 to get a total of 14,145m². This works out to about 3.9 acres - far below our target of 5 acres. Furthermore, this would assume that our main floor areas are fully dedicated to food production which we know is not realistic. Before we estimated that total area would have to be 25% greater than the minimum or 26,980m². In addition, with 1000 personnel the floor volume per person would be about 14m² of floor space each between the two decks. In the normal world, this is very high density and even in a colony environment it may be too crowded- somewhat arbitrarily I would set this figure to 15m² per person. Even if we could drastically improve our food growing efficiency (perhaps by farming on both levels- and using much more aggressive agricultural techniques), for a multi-century voyage, 8m diameter is just too small even if it is offset by the large 1.26km circumference. Therefore, we will need to look at various other size variations when calculating our starship mass. Let us next calculate the volume in our torus.

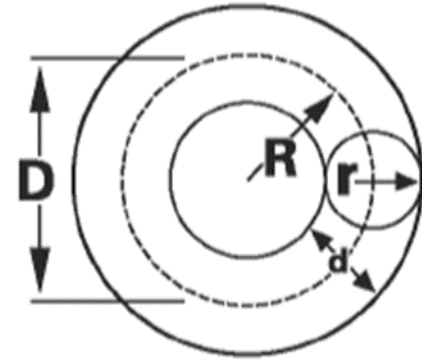


FIGURE 12-10 TORUS GEOMETRY

$$\text{EQUATION 12-7 } V = 2\pi^2 Rr^2 = 19.739Rr^2 = \frac{\pi^4}{4} Dd^2$$

Where:

$V = \text{Volume}$

$$\text{EQUATION 12-8 } A = 4\pi^2 Rr = 39.478Rr = \pi^2 Dd = 9.8696Dd$$

For our minimal quantities we require 100m³ per person for a volume, 26,980 m² for crops, habitation, work and play spaces plus 15000 for reasonable floor density (15m² for each colonists). Running the numbers for various diameter hulls we generate the following specifications:

Diameter (m)	8	10	12	15	20	25	40
Torus Volume (m³)	63,481	99,190	142,833	223,176	396,758	619,935	1,587,032
Volume Per Person (Minimum 100m³)	63.48	99.19	142.83	223.18	396.76	619.93	1587.03
Floor Area(Total including Farming) (Minimum 26980m²)	14,145	18,186	22,227	28,289	38,393	48,496	78,806
Floor Area Per Person (m²)(Minimum 15m²)	14.14	18.19	22.23	28.29	38.39	48.50	78.81

TABLE 12-3 TORUS SIZE OPTIMIZATION

Green indicates acceptable dimensions based on the parameters we have laid out. Based on this we could probably survive with a 15m diameter hull. This provides the target 100m^3 per person volume, the $26,980\text{m}^2$ minimum required for living area and crops, and 16m^2 for personnel space.

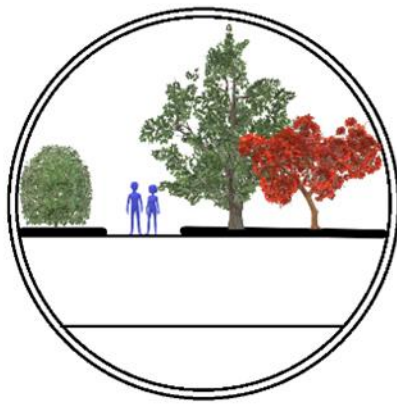


FIGURE 12-11 12 METER TORUS

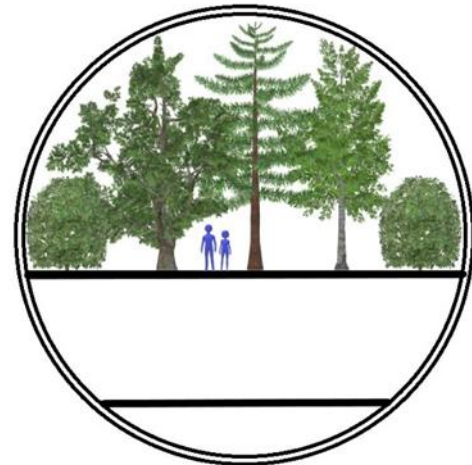


FIGURE 12-12 15 METER TORUS

What material will we make our Starship Out of?

We have several options on what to build our Starship out of. The criteria for our selection:

- Strong
- Relatively lightweight
- Corrosion Resistance
- Flexibility
- Easy to fabricate, shape and weld.
- Raw materials are relatively available.

Not all materials possess the desired characteristics in all areas, but we do have a fair selection that could fit the bill. Some materials we could consider:

- Steel- Strong but heavy; corrodes; stiffer than aluminum; easier to weld; durable
- Aluminum- 1/3 the weight of steel; no corrosion; more malleable than steel; softer and weaker than steel; requires more energy to fabricate.
- Titanium- stronger than aluminum but lighter than steel; difficult to shape and weld
- Stainless Steel- difficult to fabricate; heavier and stiffer than aluminum; corrosion resistant
- Composites- difficult to obtain raw materials and fabricate; very light and strong- frequently lighter than aluminum and stronger than steel.

Each has different advantages and disadvantages, but all could be made to work. Further analysis would need to be done to balance the different weights, properties, and ease of extracting, refining and manufacturing. The Space Settlements working group selected aluminum as the material of choice and for simplicity I will do the same.

How thick should the hull be?

The thickness of the hull is driven by the need to resist the internal atmospheric pressure, and the stress caused by the pseudo gravity on the structure. On a 10,000-year voyage we may also consider a overall robust structure that would resist punctures or accidents. We would not want our erstwhile astronauts to be banging on a pipe with a sledgehammer, to drop the sledge and puncture a hole in the hull. This spacecraft will be home for hundreds of people for thousands of years. Frailty should not be one of the concerns.

Some typical thickness of some vehicles

- Aircraft fuselage– 1-2mm- Aluminum
- SpaceX Starship- 3-4mm- Stainless Steel
- Large ships- 6mm for destroyers to 20mm for large vessel- Steel
- Submarine- 51.5-76 mm Steel

There are two design paths for building the shell of the torus, the stressed skin or the rib system. The advantage of stressed skin is that it is more efficient and hence lighter than the rib system as the skin carries all loads. The biggest disadvantage is that the skin will be thicker, and perhaps more difficult to manufacture or form. In addition, whatever internal structures are built (floor, buildings, equipment) are more directly tied to the skin which may further complicate their construction.

The space settlement design study chose aluminum for their Stanford Torus as the material of preference and a hybrid design of both a stressed skin (for most of the shell) and rib system (for the areas that had openings to allow sunlight in). To calculate the required material thickness we use the following formulas:

MERIDIONAL STRESS **EQUATION 12-9** $t_m = \frac{p_o r}{\sigma_w}$

HOOP STRESS **EQUATION 12-10** $t_h = \frac{\left(\frac{p_o}{2}\right)\left(\frac{r}{R}\right) + \left(\frac{p_g}{\pi}\right)}{(\sigma_w - \rho R)} R$

Where $p_o = \text{atmospheric pressure of torus}$

$p_g = \text{equivalent pressure of pseudogravity}$

$\rho = \text{density of structural material}$

$R = \text{major radius}$

$r = \text{minor radius}$

$\sigma_w = \text{working stress}$

The t_m is strictly the stress needed to contain the atmospheric pressure. t_h is the stress required to handle both the internal pressure as well as the internal mass.

In the Space Settlements study the shell material was aluminum with a $\rho = 2.7 \frac{t}{m^3}$. The equivalent for Steel would be about $7.87 \frac{t}{m^3}$. The Stanford Torus was designed with an atmospheric pressure $p_o = \frac{1}{2} \text{earth normal}$, or 51.7kPa. The study also calculated a $p_g = 7.66kPa$. This was calculated by taking the total internal mass (calculated at 530,00t), multiplying by the acceleration of gravity to convert to force, and spreading this out over the internal area of 678,000 m².

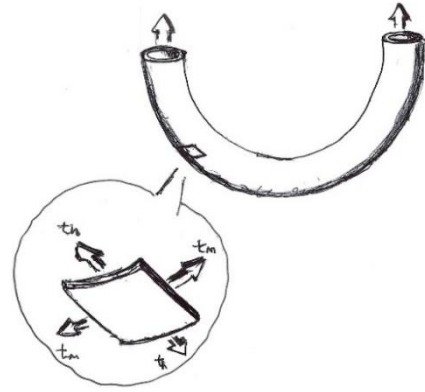


FIGURE 12-13 MERIDIONAL AND HOOP STRESS

The working stress for aluminum was set at $\sigma_w = 200MPa$. (Johnson & Holbrow, 1977, p. 111). This seems on the low side - many aluminum alloys are far stronger- but was probably done to be conservative. Steel and aluminum have a wide variety of alloys and the working stress varies tremendously depending on which is selected. Some steels are weaker than certain aluminum alloys, though the strongest steels are stronger than strongest aluminum alloys. Consistent throughout all alloys steel is much heavier- about three times higher than aluminum. Since the properties of aluminum and steel and the many alloys vary so much, considerable thought would need to be put into making the selection as to which material would be better. Using aluminum for the Stanford torus the following were calculated (Johnson & Holbrow, 1977, p. 112):

$$t_m = 16.8mm$$

$$t_h = 20.8mm$$

Our starship is going to be much smaller with an $r = \text{minor radius}$ that we determined to be 7.5m vs the 65m of the Space Settlement Survey. Our $R = \text{major radius}$ is also much smaller- 201m. Partially offsetting this we have a higher internal pressure of 80kPa.

For us to calculate the hoop stress in our starship we need to calculate the internal mass of our starship. This is a little tricky since we need to make some assumptions. There are going to be crops grown, small buildings, people and trees. I assumed that the main deck, stretched from one end of the shell (see Figure 12-15) 1.5m below centerline will be both structural and pick up the hoop stress, but also be the main internal load bearing structure.

Figure 4-3 shows a graph that was developed as part of the Space Settlement study. It shows the relationship between the shell thickness and the major radius, as well as plotting for various minor r as a ratio of the major radius. It shows the shell thickness will increase substantially as the major radius increases but it also shows that the thickness decreases as the minor radius decreases as a ratio of the major radius. In the final torus design study the team adopted a hybrid approach whereby the full hoop and radial loads were not taken up by the skin. The torus, because of the need to have a glass ceiling to let in sunlight, adopted the path where the skin took up the radial loads, and the glass dome picked up

the hoop stress with a rib system. We can do something similar as our floor, if extended throughout the whole circumference, can pick up the hoop stress.

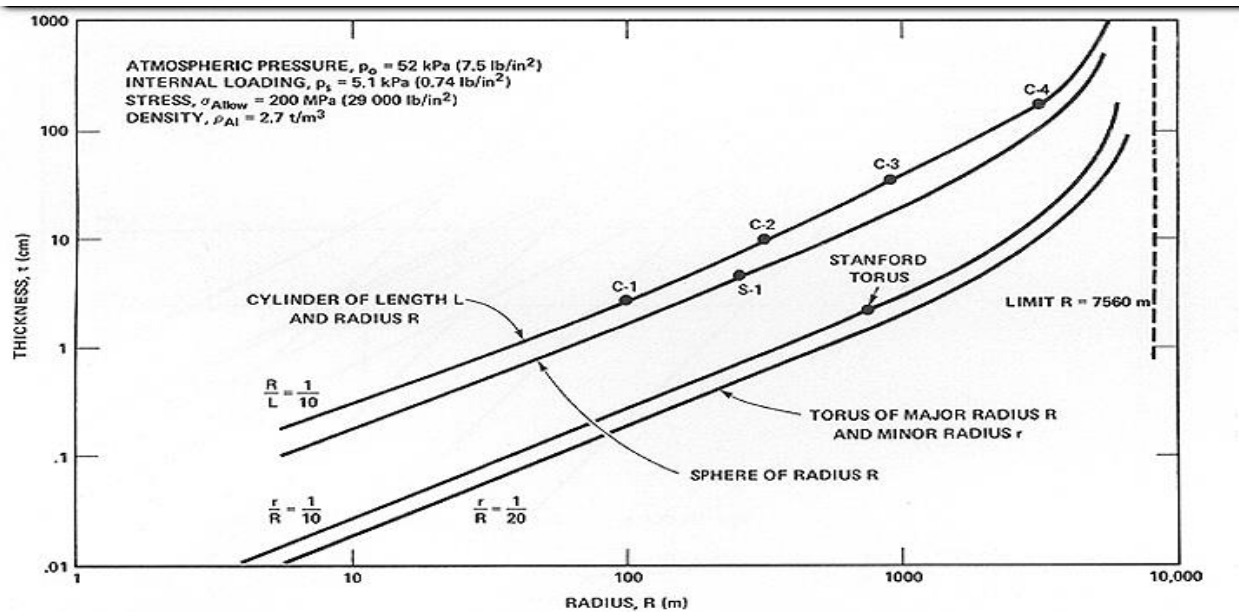


Figure 4-3.— Shell thickness as a function of radius for spheres, cylinders, and toruses spinning to produce 1 g.

FIGURE 12-14 SHELL WALL THICKNESS FOR VARIOUS SIZE SPHERES, CYLINDER AND TORUS'S (JOHNSON & HOLBROW, 1977, P. 42)

As with the Space Settlements team we will consider aluminum for our hull. This would be much lighter (about 1/3 the weight of steel) but since Aluminum is also (in general) weaker an aluminum shell will be somewhat thicker and offset some of the weight savings. An additional issue with aluminum is that it is easily deformable- as anyone who has dented an aluminum panel on their car. Related to this is that aluminum will fail during cycles of stress and strain- which can become a factor for aircraft that are pressurized and change their altitude. In our application this should be manageable... we will overdesign our structure and, as opposed to an airframe, our hull will maintain a constant pressure.

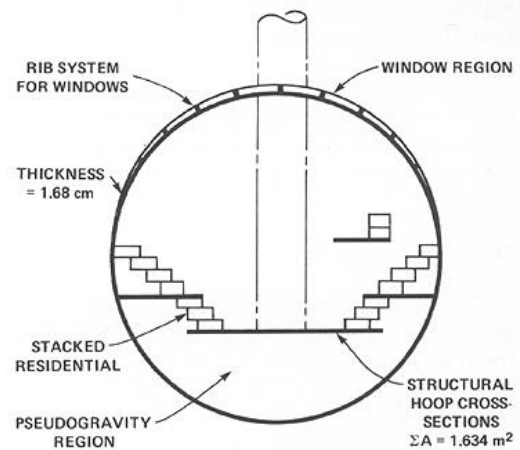


FIGURE 12-15 STANFORD TORUS CROSS SECTION

Titanium was also considered as an alternative to aluminum in the Space Settlements team assessment. According to the team, titanium would be relatively easily separated from the lunar mineral (ilmenite) (Johnson & Holbrow, 1977, p. 56). Additional cost benefit analysis will have to be done to determine our best material.

Calculating Mass of our Starship

Mass of Hull

Let us begin to calculate the mass of our hull. The mass of the torus will have the following components:

Torus shell- we will need to determine the thickness to hold in the internal atmospheric pressure as well as the stress caused by all the deadweight in the torus. Once we know the thickness, we will need to know the surface area of the shell to calculate the mass.

Torus atmosphere- we will need to calculate the volume of the torus as well as the average density of the atmosphere it will be holding.

Torus deadweight- everything that has mass and is being carried in the torus (people, dirt for farm crops, trees, buildings, supplies etc.).

Spoke weight- like the torus shell we will need to calculate a thickness and area to develop the mass of the spoke structure.

Spoke atmosphere- like the torus we will need the volume and average density of the atmosphere.

We have certain parameters that are fixed and others that we will need to vary. We have settled on our rotation rate and hence major diameter and are zeroing on a minor diameter which looks to be a minimum of 15m. The final minor diameter will play a part in determining our shell thickness. Let us start out with what we know and calculate various masses for various diameters.

The biggest unknown is the mass of the internal deadweight. The deadweight is difficult to figure out... other than the weight of the people, how much will all the equipment, machinery, structures/buildings, and supplies weigh? How about the crops? I elected to assume the main floor of the torus is covered with a layer of dirt 300mm thick that has a weight of 1700kg/m^3 . I also assumed the width of this main floor was slightly less than the diameter of the shell since I placed the main floor below the centerline either a meter or 1.5 meters below (see Fig 12-10). I used 1700 kg/m^3 for the soil mass as this is typical for topsoil. I thought 300mm was a reasonable average for thickness of soil. Certain areas (paths/walkways etc.) would have nothing on top. Others will have a lightweight structure (buildings, equipment etc.). Others may have a large tree or equipment or 500mm of soil. Is this weight reasonable? It is hard to say.

The Space Settlement survey assumed a very light, aerated soil of .3 m that only weighed 721kg/m^3 (Johnson & Holbrow, 1977, p. 95). My 1700kg/m^3 is over twice as heavy and means 300mm is quite heavy- but also makes the figures conservative and will serve as an average for everything in the torus. The Stanford Torus study had the soil weight as being about 42% of the internal mass of the torus. To this mass they added the weight of machinery, buildings, crops, people etc. While I used a similar thickness for soil since I chose such a heavy soil this should cover the weights of all those items I did not break out. With these preliminaries we have the following constant values:

Specification	Value	Unit
D_{major} (major Diameter)	402	meters

R_{major} (major Radius)	201	meters
Gravity	.9	g
ρ	2.7	t/m ³
p_o <i>= Spacecraft atmospheric pressure (80% of Sea Level value)</i>	80	kPa
Atmospheric mass (80/20 Nitrogen/Oxygen) at 80% Sea Level value(1.3kg/m SL)	1.04	Kg/m ³
σ_w = Working Pressure	200,000	kPa
Weight of Structural Material (Aluminum)	2700	Kg/m ³
Weight of “top Soil”	1700	Kg/m ³
Thickness of “top Soil”, also serves as average deadweight	300	mm
Thickness of flooring (Aluminum)	5	mm

TABLE 12-4 TORUS SPECIFICATIONS

Using these parameters, we can calculate the mass of our starship torus of various minor diameters. As with the Stanford torus I chose to use the shell skin to exclusively carry the pressure loads, and the main floor to carry the hoop stress. As an example, for a minor diameter of 8m, we have:

Meridional Stress

$$t_m = \frac{p_o r}{\sigma_w}$$

$$t_m = \frac{80kPa(7.5m)}{200,000kPa} = .003m = 3.0mm$$

For the hoop stress, we need to calculate the internal mass of the torus using:

$$t_h = \frac{\left(\frac{p_o}{2}\right)\left(\frac{r}{R}\right) + \left(\frac{p_g}{\pi}\right)}{(\sigma_w - \rho R)} R =$$

$$t_h = \frac{\left(\frac{80kPa}{2}\right)\left(\frac{7.5m}{201m}\right) + \left(\frac{6.7kPa}{\pi}\right)}{(200,000kPa - 2.7(201m))} 201m = .00413m = 4.13mm$$

Note that, because of my selection of having .9g as our gravity, this reduces the force projected onto the projection area.

Using these equations and the information in Table 12-2 let's calculate our shell thickness' for various minor radius/diameters:

	$r_{\text{minor}} = 4\text{m (dia 8m)}$	$r_{\text{minor}} = 6\text{m (d= 12m)}$	$r_{\text{minor}} = 7.5\text{ (d= 15m)}$	$R_{\text{minor}} = 12.5\text{m (d= 25m)}$
$t_m = \text{Meridional Stress}$	$t_m = 1.6\text{mm}$	$t_m = 2.4\text{mm}$	$t_m = 3\text{mm}$	$t_m = 5\text{mm}$
$t_m = \text{with safety margin}$	$t_m = 4\text{mm}$	$t_m = 4.8\text{mm}$	$t_m = 6\text{mm}$	$t_m = 10\text{mm}$
$t_h = \text{Hoop Stress}$	$t_h = 3.25\text{mm}$	$t_h = 3.77\text{mm}$	$t_h = 4.13\text{mm}$	$t_h = 5.23\text{mm}$
$t_h = \text{with Safety Margin}$	$t_h = 6.5\text{mm}$	$t_h = 8\text{mm}$	$t_h = 9\text{mm}$	$t_h = 11\text{mm}$

TABLE 12-5

While technically sufficient to handle the loads the meridional stress with 1.6mm, 2.4mm and even the 3mm shells seem excessively thin with little or no margin to allow for a puncture... especially as this will be a 10,000 year voyage and the chance that something large and heavy, whether it is a piece of equipment or machinery could puncture the hull. Therefor I have elected to say the minimal thickness for the 8m and 12m diameter structures are 4mm (a large margin of 250% for the 8m diameter structure) and a 200% for the 12m, 15m and 25m structure.

With this safety margin of the meridional stress, the hoop stress requirements are below the meridional thickness. However, again to place a safety margin to our Hoop Stress, I have doubled the required thickness and then rounded up to the nearest whole number. This will of course give us some latitude to increase our internal mass.

My preference would be to use the full calculated hoop stress with safety margin to handle the calculated load, but add, as a safety margin the two decks that run the circumference which will also handle the hoop stress loads while simultaneously serving to support the structures, building and crops. Calculating the mass of the stress skin only:

$$M_{ss} = \frac{4\pi Gr^3\eta}{\sigma - GgR} \left(\frac{P_A\eta}{2} + \frac{\Gamma}{\pi} \right)$$

$$M_{ss} = 4\pi^2 r R t_h \rho$$

$$M_{ss} = 4\pi^2 (7.5) 201 (.006) 2700 = 964,122\text{kg}$$

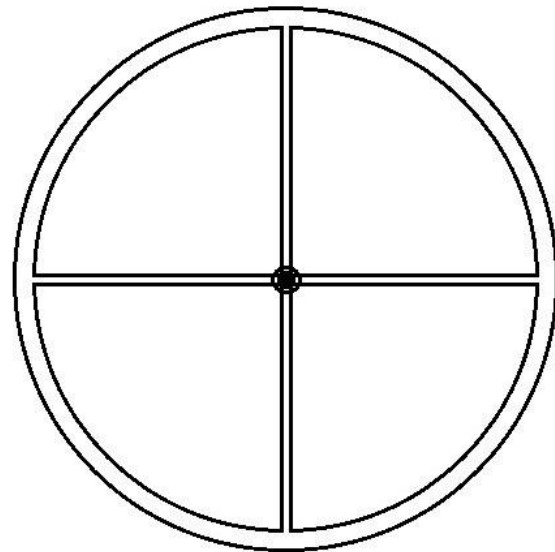


FIGURE 12-16 STARSHIP HUB PROFILE

We also need to add in the weight off the spokes- though for simplicity the torus does not need the spokes for structural integrity, so I assumed that the spokes just have the normal atmospheric pressure and just used the meridional stress for calculating the thickness of the aluminum in the spokes.

Because of our relatively small radius of the spokes, the meridional forces are quite small compared to those on the Stanford Torus. I assumed four 8m diameter spokes radiating out from a central hub, each 201m long for a total length of 804m (for simplicity I have ignored the central hub which will have additional weight, but which will also reduce the spoke length). Assuming the hubs go across the full diameter of 402m we can calculate the volume (ignoring the central axial hub) of a cylinder 804m long and 8m in diameter, for a total volume of 80,827m³ with a surface area of 20,207m². With a hub diameter of 8m we could use Table 12-3 calculation of 4mm for the aluminum thickness. Using an abundance of caution I elected to use 5mm thick aluminum.

d= Diameter	8	12	15	25	40
Shell thickness	4.0	4.8	6.0	10.0	16.0
Structure mass	342,799	617,038	964,122	2,678,117	6,855,980
Floor Deadweight	7,213,800	11,335,972	14,427,601	24,733,030	40,191,174
Floor Structure Mass	229,144	360,084	458,288	785,637	1,276,661
Atmospheric Mass	65,310	146,947	229,604	637,789	1,632,739
Hub Mass	272,791	272,791	272,791	272,791	272,791
Hub Atmospheric Mas	83,155	83,155	83,155	83,155	83,155
Personnel Mass	200,000	200,000	200,000	200,000	200,000
Total Mass	8,406,999	13,015,986	16,635,561	29,390,519	50,512,499

TABLE 12-6 TORUS MASS CALCULATIONS FOR VARIOUS DIAMETERS

We need to now add the mass of the atmosphere. Using the reduced atmospheric pressure of 80% the atmospheric mass will be about 1.03 kg/m³ (standard atmospheric pressure is about 1.286 kg/m³). The internal volume of our spokes is 80,827 m³ and our total atmospheric mass will therefore be 83,155 kg or 83.155 mt. Combined with our spoke structure mass of 272,391kg we have a total of about 356 mt.

What is interesting about these calculations is that the floor deadweight (with soil) is far and away the single massive component of the structure- above 80%. Realistically, if the floor were just aluminum plating thick enough to support our colonists, our ship would be very light. In addition to growing crops, we will have buildings, structures and equipment all mounted on the floor so having an average depth of 300mm of soil is a good proxy for anything built on the floor and is probably not unreasonable.

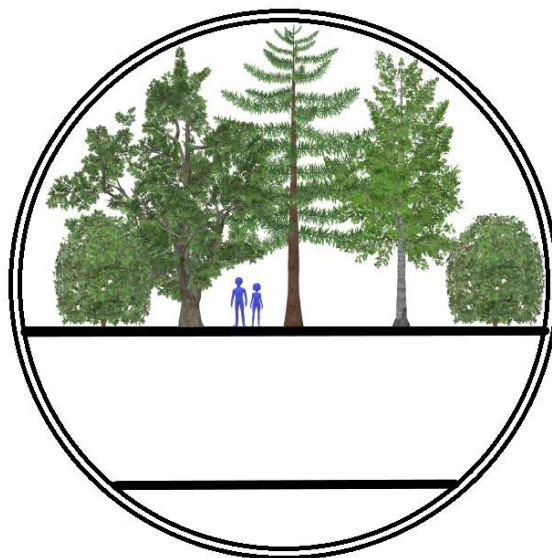


FIGURE 12-17 TYPICAL CROSS SECTION OF 15M DIAMETER TORUS

Note also, that the increase in weight is linear with increasing diameter, but the increase in atmosphere, as expected, would be a square function along with the internal volume.

Note that if we had used the smallest barrel we had considered- the 8 m barrel, the head room for a standing person would be a little more than 3m and their line of site up and down the barrel would be about 27m less in each direction or closer to 87m.

Having two, counter-rotating torus' we would mass about **34,000 MT**.



Mass of Cosmic Ray Shielding

To determine what the specific mass is the appropriate shielding depends on exactly how much radiation you are willing to expose the crew to, the materials selected to act as shielding, and your exact spacecraft shape and design. The major problem with shielding is that it quickly becomes tremendously heavy. Assume we have a 6m thick water shield as laid out per Figure 12-17. Shielding will be offset by 1 meter from torus shell but will fully wrap around the torus with the exception of where the hub spokes cross. Even here, to minimize radiation that can come down from the hub, we will place an extension so that the shielding material mass will effectively be as if the shield wrapped around 360degrees around our torus cross section. In the case of our 15m diameter hub, the outer diameter of the shielding will be 29m and our volume of ice will be nearly 550,000m³ with a mass of 550,000 mt. This is over 16x more than the mass of both of our hulls! Furthermore, this shielding only applies to our habitat hull. Our power and industry torus would have no shielding- if we wanted equivalent shielding, we would double our m1 mass to 1,100,000mt!

This is far more mass than we have considered before for our m₁. Indeed, it is so large that it would make our m₀ an unrealistic 22 million metric tons if we keep our MR of 20! We would need to have extremely powerful engines to move such a large mass.

The question becomes if during the initial acceleration phase, can we survive with a much lower shielding level, and then start building our full up shield after the acceleration phase is complete? On the deceleration phase the same strategy would apply... after we have used up most of our reaction mass and gotten to a low relative velocity, we would start dismantling our shielding and during the last few years of the voyage our crew would be exposed to higher radiation.

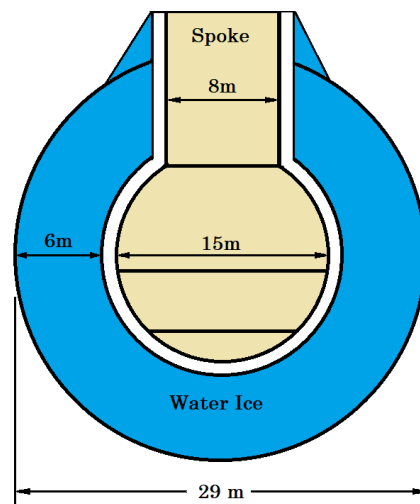


FIGURE 12-19 SIX METER COSMIC RAY PROTECTION

To determine whether this is feasible our first thing to investigate is how long we will be in our acceleration phase? If we need to travel with reduced shielding, we need to keep this period to as short a period as practical. This leads to the chicken or egg scenario- how massive we will be will determine how quickly we can accelerate. Let us assume that we use the scenario shown in Table 11-3 and use a payload mass of 100,000mt. If we went with our 10000nt engine we would accelerate to 300kps in 166 years. This would seem to be unrealistically long with minimal radiation protection.

There are a few things we can do:

- Make our starship bigger- allowing for the greater mass of the structure to provide more cosmic ray protection. Consider at least 100,000mt as the smallest for m1 payload- though ideally we would be over 600,000mt if we had a full complement of shielding mass.

- Increase our acceleration by making our thrust greater through higher mass flow and more power. This will reduce our acceleration time and hence our exposure time to higher radiation levels. High Thrust- on the order of 100,000nt will be needed.
- Reduce our spacecraft habitable volume which will reduce the area of the ship that needs radiation protection. This will be difficult as our diameter is fixed by the artificial gravity and rpm requirements. One alternative is to build a smaller diameter hub for the first few decades until the acceleration phase is over. Then the ship will be enlarged. One challenge with this is the requirement for crop and food production... a small diameter hull just can't support enough food production for a thousand-person ship as currently envisioned.
- We could reduce the final velocity of our starship which will shorten the acceleration time and allow the radiation shielding to be built sooner. This will increase our voyage time.
- Add some sort of active shielding to reduce GCR by at least 25%.

While a two-meter shield would be insufficient for our vessel based on table 4.4, a 6m shield may be excessively conservative. Our second torus will likely have little or no shielding if dedicated to a power plant and supplies but will serve as some protection for the crewed torus. If people need to work there for maintenance or manufacturing for a long period of time (days or weeks), they can sleep in small, shielded rooms. If necessary, they can be rotated out every day, reducing their annual exposure to a reasonable amount. If the two tori are only separated by a few meters the bulk of one can serve a shadow to the other, reducing the overall shielding requirement. A detailed review of the optimum shape would need to be done but we could conceive of a shield around a single torus with the second torus having little or no protection- and perhaps sacrificing some shielding on the side of the crewed torus that faces the second torus. Either way I don't see us getting away with any permanent shielding of much less than 550,000 mt.

At this stage we need to consider active shielding. Even though this has never been tried, an active shield may serve to reduce our passive shielding requirements. If the ship were given a magnetic field, perhaps driven by a superconducting current around the torus, this would serve the same purpose as the earth's magnetic field. It would divert some of the charged particles into uninhabited parts of the ship thus shielding the inhabited portion from some of these cosmic rays. Creating a very large magnetic field can be both challenging and cause its own issues, but a moderate one, that would deflect or weaken incoming particles, may be able to supplement our physical shielding. We will need a very large power plant to provide thrust and this should provide more than enough power to create and maintain a powerful shield. As mentioned in Chapter 4, a 5Mega volt current could divert about 25% of the GCRs.

Mass of power supply

We already determined the amount of power needed to run the mass driver depends on the thrust we desire and the exhaust velocity. However, this is only part of the picture.

After the mass driver, most of the power demands are driven by the need to provide light for growing crops. The earth receives about 1367 w/m² from the sun. This is peak value for a surface perpendicular to the sun's rays and above the earth's atmosphere. At the earth surface it is closer to 1120 watts- the rest being reflected or blocked. This is far in excess of what would be needed on our ark for several reasons:

- This is peak radiation flux when the sun is directly overhead. Other times of the day it is less.
- Daylight is only half the day- the other half is nighttime when the light needs would be zero. Note that certain agricultural areas may choose to have illumination for 24/7 to increase yields. Nevertheless, the point remains that, for at least part of the ship, illumination will not be 24/7.
- 1120W/m² is far in excess of what humans need to see. Typical rates for a home, office, or industrial settings work out to between 10-30 W/m².
- Much of the light hitting the earth is in the infrared- that is why our face feels warm when we face the sun. However, infrared is not needed for growing plants or to see. About 52-55% of the light hitting the earth is infrared.
- Peak Sunlight illumination is about 100,000 lux per square meter. Photosynthesis increases with intensity but levels off at about 10,000 lux. Lux is different than watts- Lux is a measure of illuminance with the power weighted at each wavelength, vs watts which is the total received radiant flux. For simplicity we can say that if peak solar flux is about 1400 w/m² and peak sunlight is about 100,000 lux then each watt equals about 71lux. Therefore 10,000 Lux works out to about 140 W/m².

Agricultural areas would probably be slightly more than this average, but this would be offset by office and building areas which would be considerably less. In addition, for office/living areas the lighting would be on for only half the day to mimic the diurnal cycles on earth. To this number we need to factor in the inefficiencies of LEDs.

Using our 15m barrel size torus, we have approximately 30,000m² to illuminate- but this is worst case as over 5000m² will be non-crop growing areas that will likely not be illuminated 24/7. The worst-case lighting requirements would therefore be approximately 4.2million Watts. A typical LED is about 30% efficient. Taking this into account and rounding it we would need about 14MW. Power for all other purposes (manufacturing, pumps, heating and cooling) will increase this but I don't believe substantially. For estimating purposes, I will put the full power requirement at 15MW.

Using our rule of thumb of our power supply generating 20W per kg, our power supply just for lighting our torus would mass about 750,000 kg or 750mt- quite reasonable. Earlier I stated it is desirable for dynamic stability reasons to have a secondary torus rotating in the opposite direction to our habitat. This secondary torus should be able to hold a power plant for both the colony and MD. The second torus can also be a storage place for supplies. Additional power for the MD will be stationed along the MD spine.

Landing/Colonizing supplies and ships

I will go into these requirements in more detail in a later chapter, but for our calculation purposes, I will assume that the colony ship will have about 4,000,000 kg worth of landing craft, colonizing supplies and unique equipment for the establishment of a colony. This will be placed in the primary and secondary torii, as well as the spine of the ship (the mass driver). This number is just a placeholder and additional analysis to identify the amount and make up of these supplies will need to be done. Some of this mass will be the landing ships (four- each about 150mt) as well as replacement materials that will be identified in later chapters.

Total mass of Landing Ships and Supplies will be about **4000 MT**

Mass of Propulsion- Mass Driver

Because of the large mass of our spacecraft, we have determined that we will need at least 10,000nt of thrust. Furthermore, as shown in Figure 11-2 and 11-3, the larger our spacecraft grows, the mass driver becomes the thruster of choice- requiring fewer packets of resupply and being more energy efficient. From this point on we will use a mass driver of 50km and **25,000 MT** as our default choice.

Total Weight of the Empty Spacecraft

We have determined that our optimum minimum size hull minor diameter is 15m. Our habitation and power torii are 34,000mt plus the weight of colonizing equipment and supplies bringing this up to 38,000mt. Our propulsion system weight is 25,000mt. Our baseline power supply (providing 15MW for the crew) weighs 750mt. Unfortunately, how heavy our final power supply is primarily driven by the power needed for our MD thruster which depends on the mass of our spacecraft and our acceleration targets and therefore our thrust.

Assuming we want to maintain a constant thrust to get us a dV of 220kps (velocity increase from 80kps→ 300kps) in about 73years we can calculate the required force of the thrusters, and thereby determine how much power we need (Figure 12-18). Our acceleration would be about $9.5 \times 10^{-5} \text{ mps}^2$. Using this to calculate power we can then figure out the size of our needed power supply assuming an 80% conversion efficiency. Graphing this we come up with Figure 12-18. What this chart shows us is that to keep a constant acceleration as we add cosmic ray protection we need to also add mass to our power supply. At the achievement of our targeted goal of 550,000mt of cosmic ray protection, our total vehicle mass will be just over 850,000mt. After this break point, all gains in mass (if we desired) would be due to a larger power supply which could be used to increase our target acceleration.

We can run this analysis for different power plant efficiencies. If we reduced our power plant efficiency to only 10W/kg for our vessels minimal cruise mass would increase to over 1,500,000mt by the time we reached our target 550,000mt Cosmic Ray protection. Similarly, if we increased our power plant efficiency to 100W/kg our total ship mass would be down to about 650,000mt- 550,000mt being for Cosmic Ray protection. This tells us that watts per kg is a major influence on our final mass.

Note that in the analysis we included the fact that 8000mt of power supply is in the second habitation module. If we assume that more of the second module is dedicated to power, we can further reduce our power supply mass's and use all of this savings for cosmic ray protection.

We need to settle on a thrust so we can determine a power requirement. Keeping in mind that the mass of the spacecraft needs to be kept to a minimal so as to be able to maximize our powered maneuver, we need to settle on an initial mass. After looking at many alternatives and the results of Figure 12-20 I settled on a mass flow rate of .19kg/sec. This means a one kg projectile would be fired every 5.25seconds requiring 925million joules. Using a MD efficiency of 80% we will need just under a 1.2GWe power supply- rounded to 1.2GWe to account for the 15MWe requirement for the colonists. At 20W/kg we will have a power supply mass of 60,000mt.

If we use this figure for a power supply and assume a vessel mass up to 200,000 mt gives us 85,000mt of shielding with no adjustments to any of our other vehicle masses. This is about 15% of the recommended shielding amount but may be the most we can provide while trying to keep our m_1 reasonable. Every ton of mass that is eliminated from our habitation module, power supply, or propulsion unit can be used for cosmic ray protection.

As discussed in Chapter 4, a five megavolt active shield system could reduce GCRs by 25%. Even though five megavolts is much larger than what can be built on a small spacecraft, on a large 200,000mt starship with 1.2GW powerplant, it should be feasible. This, combined with the 85mt passive shielding may mitigate enough of the radiation hazard to make the radiation levels acceptable for the first few decades.

Other alternatives to either shorten our radiation exposure times or increase our radiation protection are to reduce our dV to 170 kps (with the original powered maneuver we will now achieve 250kps total) and either get to our target velocity quicker (about 57 years) or if we stick to our original 73 years, a slower acceleration, smaller powerplant but be able to dedicate 98,600 mt to cosmic ray protection.

For now, assuming a m_1 mass of 200,000 mt, a 73 year acceleration and assuming a MD efficiency of 80% our total mass of our power supply (including our crew 750mt power we would come up with the following breakdown:

	MT	Notes
Torus (2)	38,000	Habitation Torus and Power/Industry Torus. 8000mt reactor mass is included in power torus
Power Source	52,000	60000mt total: 750mt for crew torus; 59,400mt for mass driver, minus 8000mt carried in second torus
Radiation Shielding	85,000	Supplemented by active shielding
Propulsion System	25,000	50km mass driver; 10000sec Specific Impulse
Colonizing Supplies	4,000	Includes four Landing Craft of 150mt each

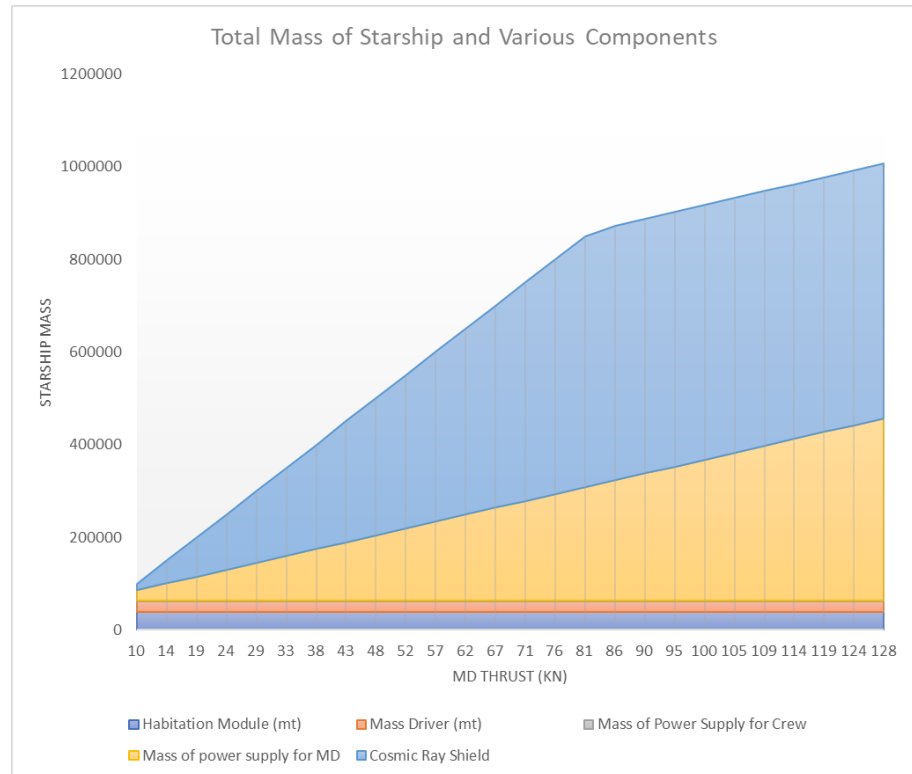


FIGURE 12-20 MASS WITH INCREASING COSMIC RAY PROTECTION AND POWER

Total m₁	200,000	
Reaction Mass for Deceleration	3,800,000	The additional mass will also serve as cosmic ray shielding
m₀	4,000,000	Assume mass ratio of 20

TABLE 12-7 MASS OF VARIOUS STARSHIP COMPONENTS

If we had started our voyage with our original full Cosmic Ray Protection of about 550,000mt our m_1 would have been about 900,000mt and our m_0 would have been about 18million mt. This is truly massive but let us consider if we did not pick up our outbound reaction mass. Then using our typical mass ratio our starting out size would have been 20x more or 360 million mt. 360 million metric tons is the equivalent of about 3250 aircraft carriers or for an asteroid with a SG of 2.5 about 650m in diameter.

We can reduce our MD size considerably if we reduce our Starship MD specific impulse since this will lead to a smaller and less massive MD as well as power supply- but as we saw in Figure 11-2 and 11-3 we would need far more reaction mass to achieve our dV targets. A reduced MD would however permit more mass for cosmic ray protection. Besides a de-optimized (small) mass driver and minimal radiation protection we may be able to save on our torus weight by not having all our structure assembled until we are done with our acceleration phase. Cost benefit analysis will need to be done, but because of the tremendous mass of our cosmic radiation protection, as well as our requirement for a thousand person crew, we will never be able to have a small starship.

With a target m_1 of 200,000mt let's build our starship. The parameters we have settled on:

- Target final velocity of 300kps
 - o Stage One velocity dV of 80kps (per the sun diver maneuver)
 - o Stage Two velocity dV of 220kps with mass driver
- $m_{1Cruise}$ of 200,000mt (per Table 12-5)
- m_0 of 4,000,000mt
- Isp of 10,000
- Average Crew 1000
- Thrust 19,000nt; Mass Flow $\dot{m}$ = .19kg/sec or 5992mt per year
- Steady State power requirement 15MW
- When under thrust our power requirement is 1.2GW

The most significant problem is that at the very beginning and end of the voyage the radiation exposure to the colonists would be high. However, even at a minimum we will always have about 85,000mt of passive shielding- or about 15% of our recommended as well as some active shielding. Also, on deceleration the shielding would not be reduced instantaneously. Using our mass ejection rate of .19kg every sec and expending 5,992MT every year we would consume our 85% of our shielding in 80 years- but that shielding would only gradually be compromised during the last 78 years of our voyage- and at the end we would still finish with our baseline 85,000mt of shielding. As with the OB colonists, we would need to keep some areas as consolidated safe zones where people would spend most of their time near the end of the voyage.

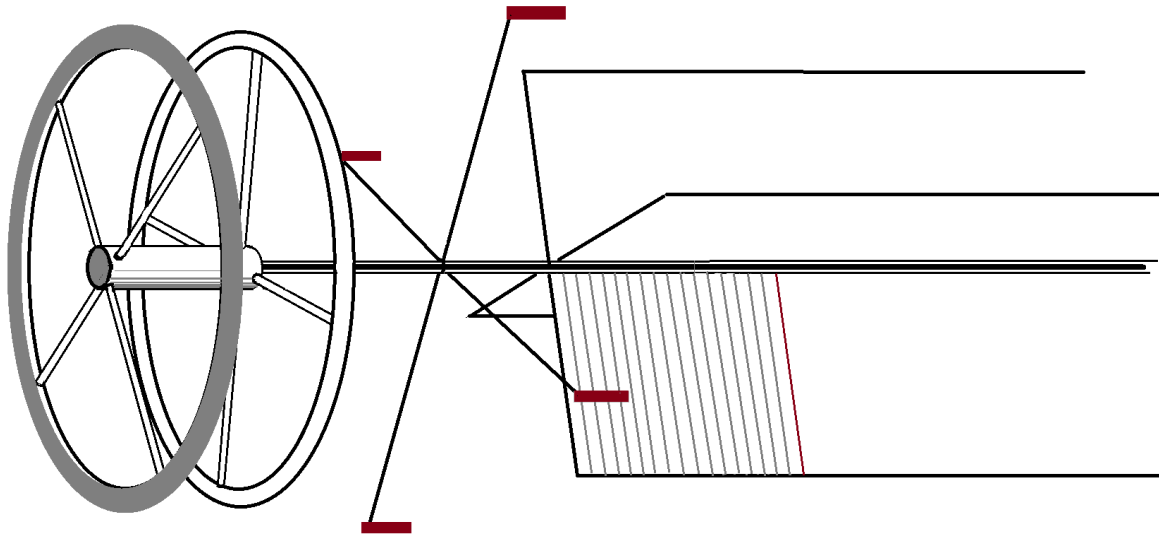


FIGURE 12-21 NOTIONAL STARSHIP WITH TORII, PACKET CAPTURE SYSTEM AND POWER PLANT RADIATORS (NOT TO SCALE)

Summary and Conclusions

We have finally settled on an overall architecture with an initial m_1 of about 200,000mt. This was determined to be the lightest we could develop for a crew of 1000 and a minimal level of radiation protection that was also able to perform a sizeable Oberth maneuver. Our mission now consists of 8 phases:

Phase 1: Year 0-4- Leaving the Earth with a colony ship to a resource rich asteroid. (Chapter 13).

Phase 2: Year 5-8- Starship would be built using asteroid resources. At the end of this time what is left of the asteroid and our starship would be decelerated to drop toward the sun (Chapter 13).

Phase 3: Year 9-13- After a several year approach to the sun a 10kps powered maneuver would be performed to give us a hyperbolic escape velocity of 80kps (as done with Saturn VIIC). Starship mass ($m_{1cruise}$) will be 200,000mt at the end of the powered maneuver (Chapter 13).

Phase 4- Year 14-87- Outbound acceleration with packet supplied mass to add dV of 220kps for a total velocity of 300kps (Chapter 14).

Phase 5- Years 87-721- Outbound cruise with packet resupply- ship will have radiation shielding built up to full 550,000mt and ship expanded. Ship will add mass until it reaches the target MR of 20. Final m_0 mass will be 4million mt (Chapter 14).

Phase 6- Years 722-10,000 Cruise for approximately 9000 years (Chapter 15).

Phase 7- Years 10,000-10,634- Deceleration from 300kps will take about 634 years. The final mass will be about 200,000mt (Chapter 15).

Phase 8- Colonization (Chapter 15).

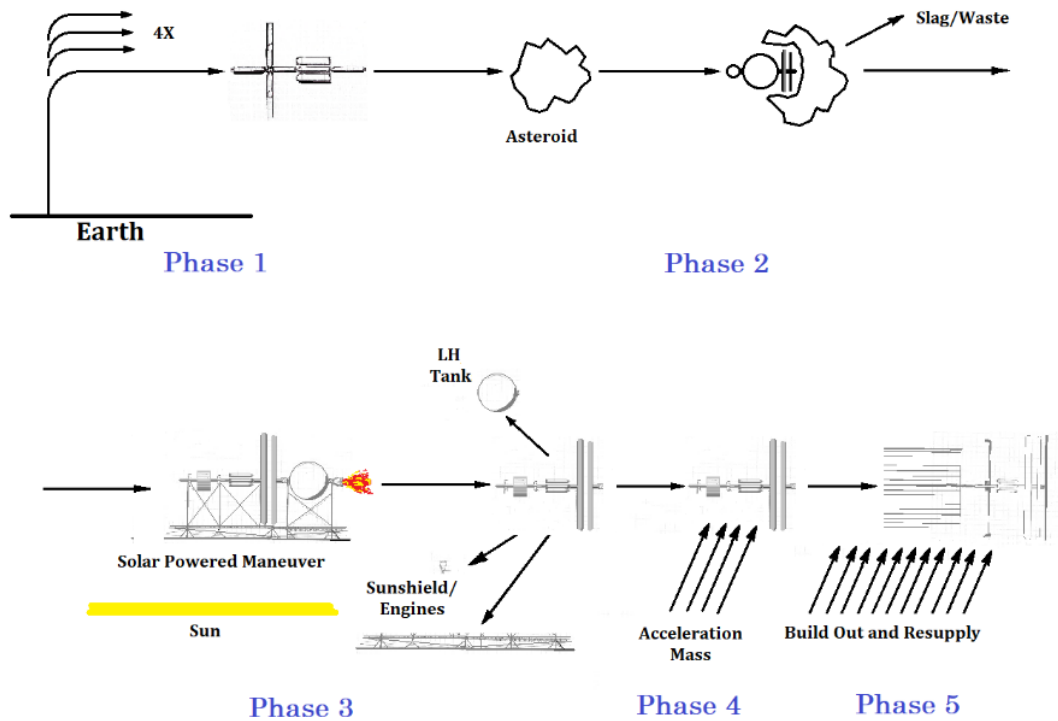


FIGURE 12-22 MISSION PROFILE

Chapter 13- Phase 1-3: The First 13 Years

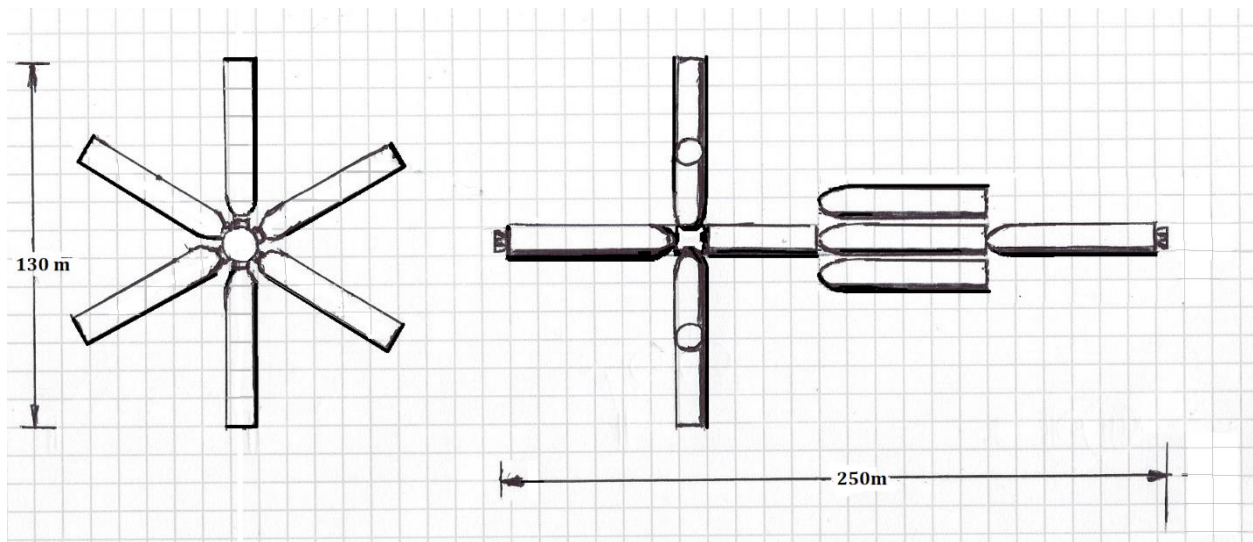


FIGURE 13-1 ASTEROID COLONIZING SHIP (ONE OF FOUR)

We have come a long way and it has not been easy. Designing a Starship required both compromise and continuous refinement- as well as considerable extrapolation of industrial and engineering capabilities. In prior chapters we identified what appears, at least in this century, the most reasonable approach. With every chapter we encountered new problems and issues that required constant engineering refinement and changes in direction. Frequently there was no single solution to address multiple problems but only a series of solutions that whittled away at the issues.

In this chapter we will incorporate all the lessons learned and pull it all together by adding some details to Phase 1 through Phase 3 of our mission.

In Chapter 10 we introduced the concept of refueling enroute as well as a two-stage starship. In Chapter 11 we looked at what a crewed starship would weigh and determined the minimal starting mass would be 200,000nmt. We then proposed an eight Phase mission architecture. In this chapter we will look at the first three phases:

- Phase 1: Build in earth orbit and launch large interplanetary spacecraft to carry our colonizers and equipment to a large water rich asteroid.
- Phase 2 Develop a small colony on a water rich asteroid and change the asteroids trajectory to perform a powered sun diver maneuver. The colony would:
 - o Do an extensive mining operation.
 - o Develop refining operation- separate out the metals and the volatiles.
 - o Have manufacturing capabilities to fabricate the bulk of the starship, including the torus and most of the power plants
 - o Mine the water and separate out the hydrogen (and oxygen if needed) via electrolysis

- Creation and storage of hydrogen for either multiple NERVA type engines or create and store both hydrogen and oxygen in case we use an LH/LOX SSME equivalent type engine
 - Build a sunshield to protect our starship during a close sun powered approach
 - Decelerate the asteroid so that it drops down for a near approach to the sun, as well as on the proper plane to head out toward the appropriate target star.
- Phase 3- do a 10kps velocity change at the sun as part of a powered maneuver. Depending on further analysis and the feasibility of building an effective heat shield we can either perform a 3 radii or 10 radii approach. Our close solar approach will allow for a 8 hour burn 10kps burn using either NERVA or LH/LOX rockets, and we will perform an analysis to select the best one. Because of the small amount of time in extreme close proximity to the sun, a 3 radii approach may be feasible and worth it because it will provide an extra 20kps velocity gain.

Phase 1- Asteroid Colonizing Ships Alpha- Delta- Years 0-4- Launching from Earth

The first phase is to build four colony ships in earth orbit. Each of these colony ships will be made of 10 ship hulls (along with four supplemental fuel tanks) launched from earth that will be joined together in orbit. The colony ships will either use a high-performance LH/LOX engine (similar to the SSME) or a Nuclear Thermal (similar to NERVA) but this will need to be determined. Either way, a large Hydrogen tank will be required. Each ship hull will be similar to the SpaceX Starship except they will be larger (12m diameter) and longer (60m) because hydrogen is so much less dense than the SpaceX methane and therefore will require larger tanks. Each of these 10 hulls and four supplemental tanks will be customized both on earth, but also in orbit, depending on the role that they will assume (see Table 13-2). I would also anticipate that since these ships (except for one hull) will never be required to reenter the atmosphere and be reused will not need to be as robust as the SpaceX Starship and will likely be made of an aluminum alloy vs Stainless Steel.

The goal of these colony ships is to carry the colonists along with their equipment from earth orbit to a water rich asteroid or mineral rich comet in the asteroid belt. To provide redundancy, each colony ship will be almost identical with its sisters.

Because I lack creativity, I will just call the four asteroid colony ships Alpha, Beta, Gamma, Delta. Each of these assembled Colony ships will have the following performance capabilities:

Capabilities		Comments
dV Capabilities	10 kps	Ability to get to Asteroid belt out to Jupiter within 2-4 years
Colonists	250	Each of the four ships will carry 250 colonists
m1 mass	3000 mt	The ten core component ship hulls will total about 1250 mt; Supplies, colonists, and

		equipment will equal about 1500mt. Balance will be for the four fuel tanks.
Ship habitable volume	20000m ³	4 habitation hulls plus hub. In addition, small volume of space in 2 Power Plants and Shuttle craft hull. Hulls dedicated to fuel will be very lightweight- about 63mt each.
Pseudo gravity	Varies	6 hulls will rotate around a hub; four habitable hulls, plus two nuclear power plant hulls
Power	4 MW (only 200 kw generated during the voyage)	Two 2MW plants will be located in 2 hulls but full power will not be needed until arriving at Asteroid. One plant will be active at 10% capacity
m0 mass	LH/LOX- 24,990 mt Nuclear- 8,312 mt	Varies depending on Isp: LH/LOX Isp of 460- MR 8.33 Nuclear Isp 1000- MR 2.77

TABLE 13-1 INTERPLANETARY SHIP ALPHA

Each of the colony ships begin as 10 Starship equivalent size rockets launched from earth and assembled and joined together in orbit. As opposed to the SpaceX Starship, they will use LH/LOX on ascent. The ships, when joined together will have nearly 20,000m³ of habitable space and will have 250 personnel. This is tight but unavoidable- it works out to about 80m³ per person. This space will also be filled up with equipment and supplies so in actuality the space available per person will be smaller. Nuclear subs have less so this should be doable based on a likely 2-4 year voyage.

Each rocket hull is going to be launched from earth as the second stage of an LH/LOX rocket, similar in performance but slightly larger than the SpaceX starship to take into account the need for larger hydrogen fuel tanks vs the Methane tanks on the SpaceX hull. I assume a 12m diameter rocket.

Each component empty hull will weigh 125 mt on average. Seven of the hulls will also carry an average of 250mt of supplies/equipment/parts each (provided by additional supply missions from the earth). Three of the hulls will be predominantly dedicated to fuel tanks and will have four additional tanks attached to store the required fuel and oxygen if needed. Depending on whether we go with an LH/LOX engines or an advanced Nerva, will drive our mass ratios. As will be shown later, for a LH/LOX spacecraft we will need almost 15,500 mt of LH/LOX, or about 5300 mt of LH if a nuclear-powered spacecraft. Using our 6 to one ratio for the LH/LOX combination, we will need 2214mt of LH and 13,286mt of LOX. Based on our rule of thumb for LH density of 70.85kg/m³, we will need a tank(s) of 31,250m³. The much denser Oxygen, using 1141kg/m³ would need a tank 11,644m³. Using three stripped down hulls along the central core, we will strap four even lighter tanks of similar dimensions- about 60m long by 12m wide each spacecraft with about 6500m³ of volume for hydrogen or oxygen. All told we would need about 7 tanks to hold our fuel for our LH/LOX version. For our nuclear thermal rocket LH tank, we will need a much larger hydrogen tank... 74,806m³ requiring 12m cylindrical tanks about 662m long- or the equivalent of almost 12 tanks.

To provide total of 1500mt of supplies as well as the fuel, as well as whatever equipment and supplies are needed to modify and assembler our colony ships there will be about 47 additional launches per colony ship in the case of the NERVA+ configuration or closer to 115 additional launches for the LH/LOX version (assuming a Starship equivalent type vehicle bringing up 150mt at a time).

The ten hulls/four tanks that make up each ship will consist of:

Ship #1 ALPHA Hull	Name of module	Specifications	Modifications in orbit
1-4	Habitation Modules	Volume- 4000m ³ habitation each; simulated gravity; five decks; will have 62/63 person per hull	Fuel tanks will be opened up, decks installed and made available for habitation. Each of the four primary habitable hulls will have 5 decks. Engines will be removed
5	Power	2 MW; simulated gravity; 500m ³ habitable space	Reactor will be at 10% power generation; cooling fins deployed. 100kw power. Engines removed.
6	Power	2 MW; simulated gravity; 500m ³ habitable space	Idle and back up. Engines removed.
7	Shuttle; Supplies	Will have 1000m ³ of habitable space but will be filled with supplies.	Will retain three engines. Supplies. This hull will be used for landing/colonizing ship at target star
8	Docking adapter and Fuel	2000m ³	Docking adapter. 4,000 mt
9	Fuel	Stretched Hull	Dedicated Fuel; if LH/LOX engines, will need additional fuel tanks attached.6500m ³ .
10	Propulsion and Fuel; Four Engines	Stretched Hull	6,000 mt fuel; Three Engines retained
11-14	Fuel	Stretched Hull	6500m3 fuel each. Attached around Hull 9

TABLE 13-2 INTERPLANETARY SATURN CA (ALPHA)

Six of the hulls, minus their engines, will be joined to a central adapter module and ship provided by the seventh ship. Four of the six hulls will have their insides modified for habitation- with a five decks, 12m in diameter and about 35m tall each hull will provide 4000m³ of living space for a total of 16,000m³ . Two of the six hulls will have mostly idled power plants of 2 MW each peak electric output. The assembled ship will be spun at 3rpm to provide pseudo gravity for the mission to a suitable asteroid. The other hulls will be attached at 90deg angle along the x axis. Note, as was pointed out when designing our torus, this configuration is not stable and will occasionally require either active intervention (retro-rockets) or large gyroscopes, to keep stable.

The seventh hull will be an intact rocket launched from earth but available for storage and habitation space. This hull will keep its main engines and will be carried along the starships 10,000-year voyage as one of the colony landing ships. This hull should probably be designed with reentry tiles- and may be made of Stainless Steel for durability.

The eighth hull will carry the central docking adapter to which the six hulls will be attached and spun around. The rest of this ship hull will be primarily fuel.

The ninth hull will have its engines removed on achieving orbit and will be used exclusively for fuel. Any additional fuel tanks needed will be attached to this hull.

The last hull will be identical with the ninth except that it will retain its engines and be used for earth escape.

Around the ninth hull will be strapped four stretched tanks minus all equipment and engines. As the ship exits earth orbit these tanks will be ejected.

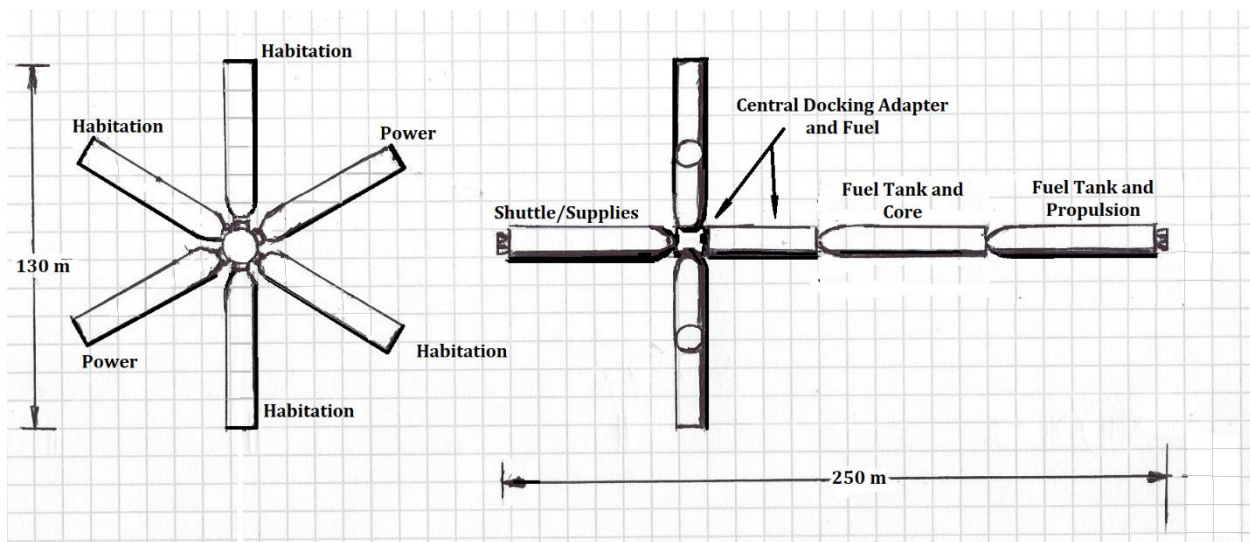


FIGURE 13-2 SPACESHIP ALPHA LAYOUT WITHOUT SUPPLEMENTAL FUEL/OXIDIZER TANKS

Total mass when leaving earth orbit will be on the order of 8300mt for the NERVA + version, or almost 18,500mt for the LH/LOX version. The m1 of the assembled ship for both versions will be 3000mt. We will determine which engine type is optimum in a later section of this chapter but for now, we will assume the larger LH/LOX ship. The SSME used a fuel rich mixture with a ratio of 6:1 and we will assume that our SSME+ engine operates with the same ratio. In this case we will need 3,141mt of hydrogen and 18,849mt oxygen. Because it will have a vacuum optimized nozzle and a somewhat higher chamber pressure it will have a slightly high performance. This SSME+ engine will have increased reliability and durability, and a specific impulse of 460.

Upon arrival in earth orbit, the ten spacecraft will be joined together as in Figure 13-2. Each hull will have different modifications performed to it while in orbit in preparation for the voyage. For the four habitation modules, the fuel tank internal dividers will be removed, and floor decking installed.

For gravity, my additional idea would be to rotate at 3rpm because it provides far stronger gravitational force than 2 rpm but if this proves to be too uncomfortable based on experience and additional study we would reduce this to 2rpm. Regardless, rotating at 2 or 3-rpm, each deck will have substantially different gravity depending on how far your deck is from the hub.

	Radius (around hub)	Pseudo Gravity 2rpm	Pseudo Gravity 3rpm
Deck 1	20m	.089	.201
Deck 2	24m	.107	.242
Deck 3	28m	.125	.282
Deck 4	32m	.143	.332
Deck 5	36m	.161	.362
Lowest Level (Equipment and Supplies)	55 m	.246	.554

TABLE 13-3 PSEUDO GRAVITY AT VARIOUS ROTATION RATES AND DISTANCE FROM HUB

The target asteroid must be water rich as a predominance of the supplies needed will be Hydrogen and Oxygen for the rockets. With our interstellar rocket performance of 10kps we should be able to reach any asteroid out to the orbit of Jupiter within 2-4 years.

Phase 2- Years 5-8- Asteroid Construction and Fuel Generation

During the next phase we start building our Starship on the asteroid, using the material from the asteroid. In phase 3 will determine the size of asteroid needed. By mass our biggest requirements will be hydrogen (if a NERVA type) or oxygen (if SSME type) followed by hydrogen. Hydrogen and oxygen will be obtained by separating them from water therefore it is desirable to have a water rich asteroid.

The construction will carry on through Phase 3- the end result will be 200,000 mt m1 after the powered maneuver.

The priority of events for the arriving colonists will be:

- Excavating and mining of the asteroid.
- Separating of volatiles and non-volatiles. Electrolysis will be used for creating oxygen and hydrogen.

- Separation of key materials needed for manufacturing (primarily aluminum or whatever material was selected as primary construction material) for both our starship as well as our equipment.
- Construction of the habitation and power torii.
- Construction of LH tank (or LH/LOX tanks if going with chemical engines) for the powered maneuver.
 - Nuclear Thermal Engine- 400,000mt LH tank
 - Chemical SSME equivalent Engine
 - 230,000mt LH tank
 - 1,836,000mt LOX tank
- Mounting of Engines for the asteroid redirect and powered maneuver.
 - The number of engines will be determined by how many are needed to perform our dV burn during the sun diver maneuver.
 - If the engines used to get the second stage into orbit are used (in the case of the LH/LOX version) each of these 10 ships that are combined for each colony transport should have three engines that can be removed and stored for future usage. If these ships are similar to the Space X starship, each ship would arrive in orbit with three vacuum engines. With ten ships making up our colony transport vessel we should have 30 engines that can be kept or discarded depending on our final mission architecture- or 120 engines total between the four colony ships. My initial configuration only requires keeping six engines for each colony ship- three engines are kept on hull 10 to break out of earth's orbit, and three more are kept on hull 7 which is the future colony landing ship. If it is determined that more are needed, we can keep them either attached to their respective hulls or transported as payload.
- Disposal of unused slag. Once enough material is separated for the tori and power supply, the rest will not be needed and can be disposed of to minimize the mass during the powered maneuver.
- Construction of the mass driver. The mass driver components will be built but not assembled until after the solar powered maneuver.
- Construction of a sun shield
- Construction of a 1GW power supply. If enough ^{235}U is not uncovered while mining the asteroid, additional supplies of Uranium will need to be supplied from earth or some other solar system body.

Mining and Material Separation

Mining materials in space will be required for the bulk of our starship mass. Fortunately, some of our key elements are relatively easily located and isolated. In a later chapter we will go over the specific quantities of various elements that we will need. The easiest, and the items that are most needed in bulk are the volatiles-Oxygen and Hydrogen for our rocket engines, Oxygen and Nitrogen for life support. All are available (though not always conveniently) in the solar system. Oxygen and hydrogen

would easily be obtained from water, and Nitrogen either directly from the distant solar system objects where it is frozen, or more likely from ammonia on some of the closer bodies.

Next up are the metals for construction. The asteroid is likely to be relatively poor in metals, but the sheer volume of our asteroid means that there should be sufficient quantity, except perhaps for some rare earth's materials.

The biggest challenge will likely Uranium. Mining and refining Uranium is a large operation. How much Uranium is available on an asteroid is unknown but we have some estimates from meteorites. In one analysis Stony Meteorites had 15ppb by mass and Iron Meteorites had 7ppb (Kaye, 1995). It is likely the entire asteroid will have to be processed in order to get a useful quantity of Uranium. Furthermore, these densities are far lower than is typical with Uranium Oxide Ore (Uranium combined with Oxygen- U_3O_8) on earth. A low-grade Uranium Oxide ore on earth may have **100-2500ppm** and high grade may be much higher. It is unknown if asteroids would have rich veins of Uranium Oxide or some other concentrated source as on earth. It is likely that some asteroids will have higher concentrations than our target asteroid which was selected on the basis of being water rich. If not the recovery of Uranium may be extremely difficult and impractical. Large quantities of Uranium would have to be either shipped from either earth or from other sources still to be identified. A lack of adequate source of Uranium could be a severe problem for our starship and our MMD.

One alternative that we could consider is the use of thorium for a reactor. Thorium is 3x more common on earth and likely on the moon and asteroids. However, Thorium reactors are very different in design and are not as developed as Uranium reactors- no large reactors have ever been built. Thorium could be an alternative but because of its immature development status I have not considered this throughout the rest of this book. It may be a technology for the end of the 21st or the 22nd century.

Our Phase 1 crew will need to bring all their equipment to both mine and process the materials for use. It is likely that the bulk of the asteroid mass will not be needed, and this will be disposed of before we begin our asteroid redirect operation in Phase 3.

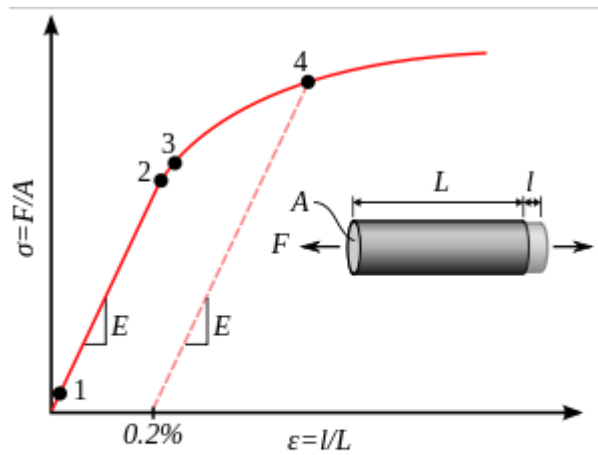
Torii Construction

The two Torii present an interesting challenge to construct but once the best technology is decided on, should be relatively easy to address. The question is how do we fabricate a complicated shape like a large torus?

The most direct way is to fabricate large aluminum (or Steel or Titanium) sheets. The making of various metals into finished products will be useful for many things, including doors, bulkheads, piping, and cables. As we have mentioned many times, currently few or none of the manufacturing techniques used on earth have been used in space. The good news is that by the time we start building for our starship 50+ years from now, Martian, and Lunar colonies should be a real thing, and they will have developed many of the technologies needed. Currently Elon Musk has a goal of colonizing Mars as a self-sustaining colony in the next 30 years or so. This will aid us immeasurably with our manufacturing capabilities when we start building our starship.

To give just a small hint of the challenges for manufacturing in space, let us look at how we would construct our habitation torus.

The easiest technique is to make sheets 4m wide, and to bend them in a hoop and weld the hoop closed to make a short cylinder. Each sheet would be about 48 meters long by 4m wide. They would be bent by a form and welded to join them together into a cylinder 4m wide and 15m in diameter. Additional cylinders would then be fabricated and welded together. An alternative related method is spiral welding of a continuous sheet.



Stress–strain curve showing typical yield behavior for nonferrous alloys. (Stress, σ , shown as a function of strain, ϵ .)

1. True elastic limit	3. Elastic limit
2. Proportionality limit	4. Offset yield strength

FIGURE 13-3

Unfortunately, from a manufacturing point of view this is not so easy. The problem is that we need to make a torus. In most cases on earth cylinders are very common and usually straight- be it an aircraft or submarine. In our case we need to bend this around to make a torus. On a smaller scale pipe can be bent into almost any shape- but 15m diameter pipe is not fabricated in this way.

We will not go into the details of pipe manufacturing but touch on a couple of the relevant points. There is no doubt that pipe will be required for various applications- including for our power plant cooling radiators as well as in our torus for moving around water and waste.

First is we need to understand the stress, strain curve and how metals behave. In Figure 13-3 we show a typical curve. What this curve shows is that between points 1 and 2 a load will cause a smooth, continuous

deformation. If a load is brought up to any point on this section of the curve and then removed the metal will shrink back to its original unloaded shape. Once we go between 3 and 4 the properties of the metal changes. If we stress the load to say point 4, the curve angle stays the same and the material will shrink, but not to its original shape. It will now be permanently deformed in its unloaded state by .2%. If a load it applied it will now deform along the new curve.

How is piping made? Piping is normally made straight or linear and then bent to suite. The pipe metal (frequently steel but also, aluminum, copper etc.) is pushed past its elastic limit and when the bending force is relieved the metal will relax into a permanently deformed position. There are limits to how sharp the bend would need to be but pipe bends where the bend radius of 4x the diameter (or less) are common.

Straight pipe can be made in a couple of ways- welded (seamed) pipe (including spiral welded) and seamless pipe.

Seamless pipe is made by taking a solid billet of steel, heating it, and while it is being rolled, pushing a piercing point through the middle. Seamless pipes are typically lighter and better for high stress applications since they are only welded were they are joined to the next section of pipe. The largest

diameter of such pipe that I have found is .4 meters. I believe the manufacturing of seamless type torus would not be practical.

Simpler, and able to make larger pipes, we may consider seamed pipe which normally consists of gradually forming the steel so that it curls together and then welding the two ends. They will have a single welded seam along its entire length.

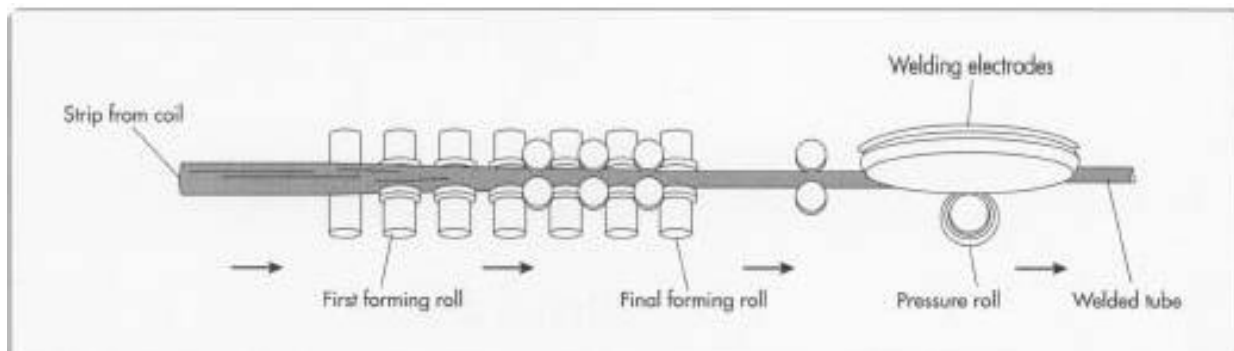


FIGURE 13-4

A wide steel (or aluminum) plate would be manufactured and bent with rollers into the correct curvature so that the two ends would meet and be welded together. As long as we feed the system with a continuous steel plate, we can continue to make our pipe. As with Seamless Pipe, diameters are limited. The pipe circumference is only as large as the steel plate feeding the process which is usually only about one or two meters wide. Larger rolls can be made but our hull will have a circumference of nearly 40m and steel plate is not made this wide. The only workable option is likely spiral welding were a continuous sheet is rolled at an angle and as it curls around is welded to itself. This sort of welded pipe can be very large in diameter and long- depending on how long the sheets are. The problem with this method is that this would make a straight tube and we need a torus. I can see two primary ways of assembling this torus.

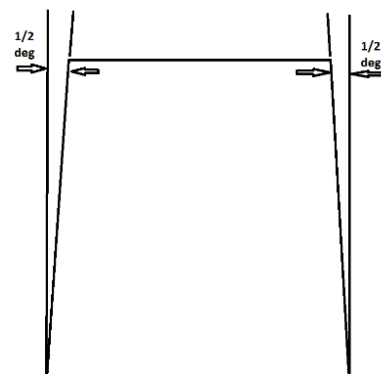


FIGURE 13-5- TORUS SECTION

The simplest method for a 201m radius torus is to roll a bunch of cylinders four meters wide, camber the ends and weld them together (similar to a short length of seamed pipe). The approximate linear length of our torus would be 1262 meters. This would work out to about 316 sections of 4 m width. Each cylinder is $1/316^{\text{th}}$ of the circumference- or a little more than one degree. If we cambered the ends of the barrel (approximately .44 degree on either end, we could weld these sections together and make our torus. Note that the inside radius of our 15m barrel section would be 193.5m and the outside would be 208.5m. This means the circumference of the top of the barrel and the bottom of the barrel are 1216 m and 1310m respectively, or 94m shorter. Since we have approximately 316 sections, the top (inner dimension) of a nominal barrel section would be approx. 297 cm shorter than the bottom.

This would be the easiest construction technique since once the cylindrical barrel sections are formed, welded at the top and chamfered to the correct angle, only a single circumferential weld would have to be done around the perimeter to join it to the next section. Aesthetically, and structurally this may not be desirable. Each of the barrel sections will have stress points where they join. In addition, the floor and layout inside the torus would likely not have these sharp bends. The inside floor would likely be a continuous aluminum or steel floor plate gradually bent around the entire circumference.

If we made a single straight cylinder (either by welding a series of 4m wide cylinder or did a spiral welding pipe) with a total length of 1263m we could try bending. The bending needed for our torus is very gradual- as we saw about 1deg for each 4 meters of length. Our Torus hull section would be about 7.5% of the radius- so would appear rather thin (as shown in Figure 12-1). The issue with this is that the aluminum, steel or other metal must be deformed permanently, and I don't see how we would be able to do such a gradual curve with a 15m cylinder. The bending jig would be huge, and I am not sure how practical it would be to bend such a large cylinder, made of relatively thick metal, into the proper shape.

Perhaps the best solution is we would develop very small panels, perhaps 4x12 m that are stamped into a properly curved shape and welded to adjacent panels. Aluminum in particular, is very easy to form (besides its light weight this is one of the reasons that it is used for cars). However, this will require far more welding.

It is possible that other manufacturing techniques, including additive manufacturing or metal vacuum-vapor deposition where an aluminum vapor is sprayed over an inflated form, could be used. All these technologies will need to be further investigated- but there is no doubt that working alternatives exist.

Finally, the tori will need some sort of active balancing system to keep the mass evenly distributed. If a meeting is held at one end of the torus, the mass of these people will cause the torus to wobble. An active water pumping system will need to be in place. I would foresee a series of 1000 liter tanks spread every 10 meters or so that would be pumped empty or filled as needed to offset these asymmetric loads. If, on average, these were filled 50% this means we would have 63mt of water tied up in our stabilizing system.

Tank Construction

The construction of the spherical tanks should be able to use many of the same techniques used in constructing the torus however the size of these tanks will be substantial. In addition, both fuel and oxidizer (if needed) tanks will need to be insulated and blocked from direct sunlight. The hydrogen tank in particular, whether it is used for the NERVA+ engine or the SSME Type engine, will be a challenge as it will need to be very large as well as maintain its temperature close to absolute zero. As noted in earlier chapters, spherical tanks are most efficient in material usage, strength, and, having the smallest outside surface area, easiest to insulate. Since we already have determined that we will have to make a relatively complicated shape like a torus, we can assume that we will also be able to make large spherical tanks.

In prior chapters we did quick rule of thumb estimates for tank mass based on surface area. As we found when designing our tori, this is not sufficient for refining our design. Using an approach similar to when

we designed our torus, but instead we use the appropriate formula for a non-rotating sphere we can calculate how thick our tank skin needs to be.

EQUATION 13-1 $\sigma_{sphere} = \frac{p_o R}{2t}$

Where $\sigma_{sphere} = stress$

Until we know the volume of oxidizer and fuel, we can't determine our Radius and will therefore not be able to calculate our tank stress or thickness. We will determine this when we describe the Phase 3 portion of the mission later in this chapter.

Engine Placement

Assuming that each ship launched from earth arrives in orbit with three engines, our 56 spacecraft will have 168 engines. This would only apply if we planned on using our SSME+ type engines. If we need to have NERVA+ engines we will have to deliver these as payload from earth, and once in orbit move them to the back of our colony ship. If using the SSME+ engine, we could either return the unneeded SSME ascent engines or dispose of them. This is an advantage of the SSME+ engine... the Colony ships are made up of the second stage rockets launched from earth they will already have their engines. No need to manufacture them or bring them along as payload.

Four of these spacecraft (identified as Hull 7 for each of the four colony ships), with their 3 engines each, would be kept on their respective hulls. These will be the ships used 10,000 years later to land on the colonizing planet or asteroid. This still leaves us with 156 engines. The four colony ships can use three engines each to break out of Earth's orbit and send the ships Alpha, Beta, Gamma, Delta on their way to the target asteroid/comet. Whether these engines still have sufficient life left on them to be used for our asteroid redirection would need to be assessed. Even without these 12 engines we would still have 144 engines with low time on them. If we are using NERVA+ we will use them for our earth breakaway and dispose of the SSME+ engines.

These engines will be used for the asteroid redirect portion of our mission. How many engines and how long they will need to burn will be determined later. However, the fuel and/or oxidizer tank size will ultimately be determined by the size needed for our powered maneuver. The asteroid redirect burn can be done over a period of weeks or months.

Our asteroid redirect burn will require a dV of about 15kps. This is very large, made even more challenging by the fact that the asteroid is likely to be very massive- in Phase 3 we will determine the mass of our required asteroid.

We will have shipped about 4MW of power on each of our 4 Colony Ships or 16MW total. Using our rule of thumb for electrolysis of 48kwh per kg of hydrogen. Assuming we use about 50% of our power for electrolysis (8MW) we could generate 167kg of hydrogen per hour- or 4mt per day. We would simultaneously liberate 8x more by mass of Oxygen. This may not be sufficient for our needs- we will need to determine general power requirements and hence fuel/oxidizer production later.

For the asteroid redirect, a large engine mount will have to be constructed to hold our engines, engine plumbing and directional actuators to be able to point the engines in the appropriate direction. The

purpose is to remove most of the asteroids orbital velocity so that we drop down to the sun with a perihelion of 3solar radii. In addition, this is the opportunity to make a plane change to put us on a trajectory that will enable us to exit the solar system toward the appropriate star.

The asteroid will be slowly rotating so if the engines either individually or on a rigid mount, should be able to be gimbaled. Furthermore, changing an asteroids orbit, even a small one, will likely require hundreds of hours of thrust. Normally engines are not designed for this but fortunately the SSME was designed to be reused so this will be a good engine for a baseline design. Similarly, NERVA engines were tested for half hour at a time. I would foresee that the engines will only fire at certain times as the asteroid rotates around its axis. If the asteroid rotates every 10 hours, we may fire only for one hour in every 10. It may take several hundred firings over many months to achieve our 15kps dV. When we calculate our engine configuration later in this chapter, we will determine how many hours of rocket firing we need to achieve our performance goal.

Waste and Slag Disposal

We need on the order of only a few hundred thousand metric tons of metal in the construction of our starship. We need far more oxygen and hydrogen (in the form of water). Unless the asteroid is unusually water rich, to obtain the necessary water we will be processing a lot of other materials including silicon, clay, metal etc. Once we finish separating all our materials, we will have a lot of materials that are unneeded- which we call slag. We would not want to keep this material because this mass would require even more reaction material to accelerate when we do our asteroid redirect. Therefore this material will be disposed of by “throwing” it off the asteroid before we begin our asteroid redirect. The asteroid has such a low gravitational force that a few mps should be sufficient to permanently dispose of this material.

Mass Driver Construction

After the power supply expansion, the starship MD is the next most challenging element. The good part would be that the Mass Driver sections should be almost identical- each section being perhaps 4 meters in length. Once one section is created, the other one should be just a copy. Once we have the required material (copper, aluminum, wiring, bracing, electronics) we will start making them in large quantities and bolt them together. The exact design would be developed on earth where it could be tested, and its manufacturing process optimized. I would doubt that the MD will be assembled until after the solar powered maneuver. It would be difficult to conduct a powered maneuver with a 25,000 mt mass driver stretching for 50km. I believe that most if not all the components will be constructed while the asteroid is being mined and during its plunge toward the sun. Assembly would occur when the starship is enroute out of the solar system. Do to radiation concerns, I believe the bolt together portion of this mission should be automated and done by robots to the greatest extent possible.

Sun Shield Construction

The sun shield will be needed to keep the direct rays of the sun off our spacecraft and LH/LOX tanks. As described in Chapter 8, I would foresee a design similar to the JWST with a highly reflective and

temperature tolerant first layer and several other layers mounted behind this- each cooler than the proceeding one. Keeping the Hydrogen liquid will be a challenge since, in some cases it will have to be maintained in liquid form for months as our spacecraft drops toward the sun. On closest approach, some active cooling of the hydrogen will likely have to be done since I am not sure that the sun shield alone will be able to keep the hydrogen at a few degrees Kelvin. The worst heating will occur during perihelion- but our ship will be traveling so fast (in excess of 200kps) that this intense period of heating will only be a couple of days. I am not sure the total mass of the sunshield- but its area would need to be able to shelter the entire spacecraft from the direct rays of the sun. Our torii is over 400m in diameter and our fuel tanks- whether Hydrogen for a Nerva+ engine or LH/LOX for a SSME+ type engine, will be quite large (though we have not figured this out yet). For a first assumption, let us assume a shield 500m x 500m in diameter- or 250,000m². We can assume the sunshield to be multiple layers- each layer would be thin (but far heavier than that required for a speculative Solar Sail). If our multiple layered and reinforcement solar shield could be built to handle the powered maneuver could mass 10kg per square meter we would mass only 2,500mt total.

Power Supply Construction

The original power supply delivered to the asteroid colony consisted of eight reactors, each one generating 2 MW for a total of 16MW. This was sufficient for our initial colonists as well as preliminary mining and processing. As we saw when calculating the mass of our power supply in Chapter 12, the starship mass driver requires 1.2GW and our power supply would need to be over 70x larger than what we originally supplied the colonists with. We will have to tremendously expand the amount of power as we go through phase 2 and phase 3. Some uranium will be extracted from our asteroid, but we may need to supplement it with supplies from earth or other sources.

Regardless, the first few years on the asteroid our power supply will need to be substantially increased. By the end of Phase 2 when we are ready for our asteroid re-direct, we will have far more power available as we get ready for powered maneuver and by the end of phase 3 we will need to have our full power available for our mass driver. Due to the tremendous quantity of Hydrogen needed to perform the asteroid redirect we will need to dedicate a lot of power for our electrolysis. If we dedicated 1GW of power to electrolysis, we would generate 500mt of hydrogen per day.

Large reactors require large cooling radiators. For our starships 1.2 GW power plant it is extremely large- 1000x larger than what we discussed in Chapter 8. Using our calculation of needing 1,836m² for one megawatt, we can now estimate we will need 2.2x10⁶ m², which works out to radiator panels almost 2.2km². The front of our spaceship, with its cosmic ray shield and meteoroid bumper will keep the back of the ship protected in a meteoroid “shadow”. For this reason, we will keep our radiator panels in the shadow of our meteoroid shield. Four “wings” each 200m wide arranged at 90deg angles from each other would sprout from our central spine and run for 2.75km down the spine. Depending on where we collect our packets, we would likely keep the power plants and radiators far away from our packet recovery system.

As with the MD, while we approach the sun and do our power maneuver, radiator panels this large will be problematic- both to shielded from the sun, as well as handle the acceleration forces during our solar maneuver. For this reason, we will probably have to dismantle a portion of our radiators that were built

for our electrolysis until we are in deep space several weeks or months after our close approach. We can expand our reactors to our 1GW target during phase 2 and 3, but would dismantle and idle them during our sun dive maneuver.

Phase 3- Years 9-13- Sundiver

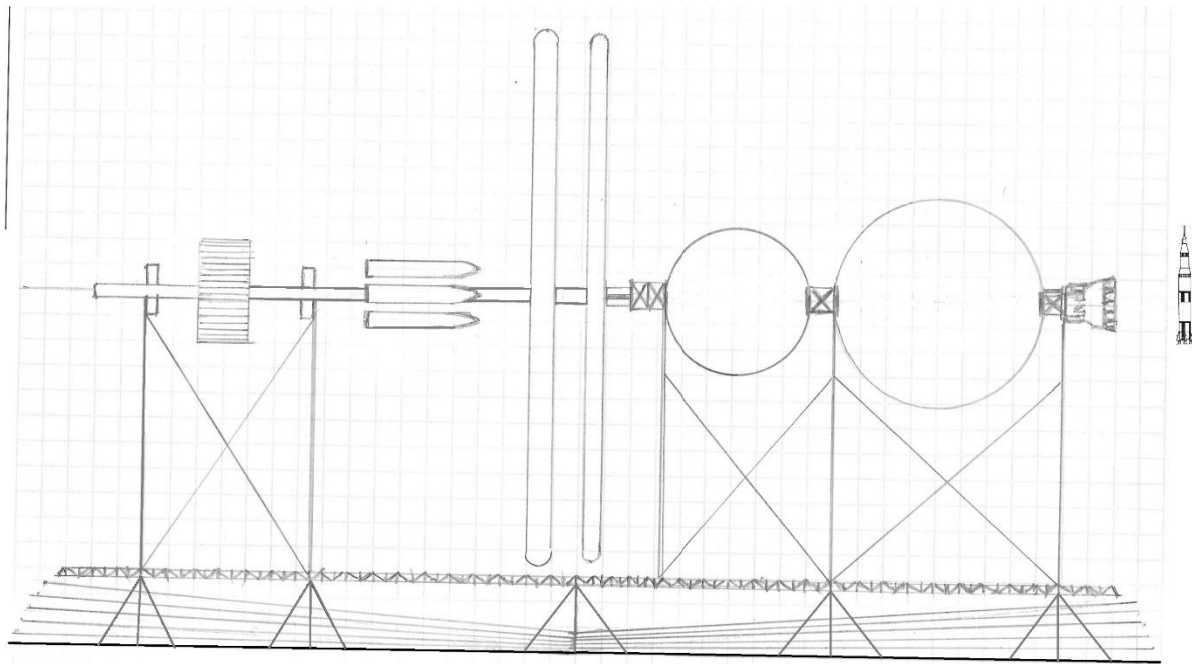


FIGURE 13-6 STARSHIP M SUNDIVER PHASE 3 (LH/LOX SSME+) VS SATURN V (TO SCALE)

There will be two trajectory changes during Phase 3- one is to decelerate our Asteroid/colony so that it drops toward the sun (as well as allows for the necessary plane change to get to the appropriate star and the second will be a powered maneuver around the sun.

The first question we need to answer is whether a nuclear rocket, or chemical (LH/LOX) rocket would be better? Depending on which we pick will determine how much oxygen and hydrogen we need, the MR and the size of the tank(s) that are needed. The answer turned out somewhat surprising.

To identify the optimum solution, we need to work backwards as the most critical phase is the burn around the sun during the powered maneuver. I chose a aggressive 3 radii approach to the sun because off the great performance numbers. At this distance we would have a final escape velocity of about 80kps if we selected a target dv of 10kps. I placed the further constraint that this delta V needs to be applied during the 8-hour period of closest approach.

The performance required for each section are now specified as:

- Slowing the Asteroid down to drop toward the sun- dV of 15 kps. This can be done intermittently over a period of several weeks or months.
- dV for sun powered maneuver- 10kps- applied within 8 hours or 28,800 seconds.

When developing the numbers, I used a 200,000mt starship m_1 mass as developed in Table 12-5. I also assume some 10,000 mt mass ejected mass at the end of our powered maneuver which consists of those items no longer needed- primarily a large sunshield, the large H₂ tank (and LOX Tank if appropriate), and the engine pack, in the first case with all the NERVA engines and in the second, SSME equivalent engines. I will need to make more assumptions to calculate how large our asteroid will need to be. Since the primary material needed will be hydrogen (whether for the NERVA+ configuration or the fuel for the LH/LOX configuration) I need to pick an asteroid that is high in water- so I selected 40% water as the asteroid composition. The required asteroid mass will be backed into based on our final payload mass after the sun maneuver which we are targeting at 210,000mt. Note that the assumption is that of 25,000mt of tanks, engine pack and sunshield some of this raw material can be used for our ship and only 10,000mt will be ejected making our final m_1 only 200,000mt.

When calculating the asteroid's composition, I assume that the remaining 60% mass is a variety of compounds including silicone, metals, carbon etc. We need only about 210,000 tons to fabricate into our colony so using the fact that 60% of the asteroid will be minerals of one sort or other, only a fraction of the asteroid mass will be needed to construct our starship- and the remaining can be dumped.

Below are the specifications for the two propulsion modes being considered:

Specifications (units)	SSME+	NERVA+
Specific Impulse (seconds)	460	1000
Ve (kps)	4.51	9.81
Thrust (MN)	2279	1150
Flow Rate (kg/sec)	515	150
Engine Mass (kg)	3200	10,000

TABLE 13-4 SSME+ AND NERVA+ COMPARISONS

Nerva+ Option

Using a specific impulse of 1000 for the NERVA means that our mass ratio will be much smaller for the powered maneuver- for a dV of 10kps the mass ratio will be about 2.77. However, the NERVA engine provides less thrust (about ½ that of the SSME) and a much lower mass flow (about 30%) than the LH/LOX version meaning it is difficult to have a short burn time that provides enough dV during the sun dive maneuver. Furthermore, since we are using nuclear thermal, we will not be needing an oxidizer, but we will need more hydrogen than the chemical engine. Since our hydrogen will come from water, we will have to process a lot more water to get the hydrogen we need and dispose of all the unneeded oxygen.

I looked at the relevant masses for the first two three phases of our mission. Running the numbers (bold bordered boxes are numbers that were plugged in- all others calculated; Green Boxes are waste products and are “dumped” overboard). Starting with a launch from earth with an m_1 of 3000mt and using the performance for a NERVA+ spacecraft the earth departure m_0 mass would be 8312mt.

The performance numbers for the nuclear engines should be reasonable- especially as this starship will be built in the later part of the 21st century. Project Timberwind from the early 1990 discussed extrapolated engines with a specific impulse of 1000 and mass flows of just slightly less- about 115kg/s vs our NERVA+ engine with a mass flow of 150kg/sec.

NERVA +											
	Description										
Phase	Launch	Earth Orbit	Asteroid Arrival	Asteroid Manufacturing		Deceleration		Acceleration		Coast	
Payload	1,750	1,750	1,750	3,000	200,000	200,000	200,000	200,000	200,000	200,000	200,000
Hulls/Ancillar	1,250	1,250	1,250		10,000	10,000	10,000	10,000	10,000	10,000	0
Asteroid				74,343,146	0		7,252,858				
O2					30,414,829	30,414,829		2,975,532			
Waste					39,919,463			3,905,385			
H2		5,313			3,801,854	3,801,854		371,941	371,941		
Total	3,000	8,313	3,000	74,346,146	74,346,146	34,426,683	7,462,858	7,462,858	581,941	210,000	200,000

TABLE 13-5 NERVA+ OPTION

The asteroid starting mass assumes that it is 40% water (on the high side for an asteroid). We back into the required asteroid mass from our final m1 target of 210,000mt at the end of the solar powered maneuver. At this point we eject about 10,000 mt. This would mostly consist of our 9,000 mt unneeded sunshield but would also include our Nerva engines (the number and total mass will be calculated) as well as our massive hydrogen tank. I assume that most of the unneeded material can be used for the colony so I only assumed 10,000mt would be ejected. If we elect to go with the NERVA+ configuration I will calculate a more precise mass for our fuel tank later.

From the required MR and m₁ mass of 210,000mt we calculate the m₀ mass at the start of our powered maneuver. Using this m₀ as a basis for calculating the m₁ of the asteroid after it performs its initial dV that causes it to drop toward the sun (asteroid orbital velocity estimated to be about 15kps) we can again back into our starting m₀ for our asteroid.

To use up our 354k mt of hydrogen fuel in 8 hours would take about 86 NERVA+ engines. At 10mt per engine, the engines alone would mass 860 mt.

Whether it is practical to build 86 large pebble bed nuclear engines is uncertain from a political and public acceptance perspective. That is a lot of radioactive material that will need to be launched from earth or developed in space.

The other engineering challenge is that to decelerate the asteroid these engines would need to operate for almost 90 hours (82 hours for the asteroid redirect and 8 hours for the powered maneuver). This does not have to be continuous but even if interrupted the overall wear and tear on the engines may be prohibitive. There will likely need to be spare engines or the ability to repair the engines or change out the fuel elements. Most nuclear engines that were tested in the mid-60's were operated for about an hour and a half so further development will need to be done. I am comfortable that we will be able to substantially increase this number, but I have concerns as to whether we would be able to extend the total operating time to of a total of 90 hours required for the solar powered maneuver and the asteroid redirect.

LH/LOX Option

Using a LH/LOX engine we assume that the LH/LOX engines are similar to the SSME- they use the same fuel/oxidizer ratio, consume the same amount of fuel per second, and mass the same. I do assume some

improvements- slight durability improvements, slight specific impulse improvement due to higher combustion chamber pressure and a vacuum optimized nozzle with the greater mass offset by improved mass for other components so total mass is unchanged. I will designate them as SSME+ to differentiate them from the normal SSME.

Because of the lower performance of the LH/LOX engine we will need a higher mass ratio. Our numbers for this configuration are:

Conventional SSME+											
Description											
Phase	Launch	Earth Orbit	Asteroid Arrival	Asteroid Manufacturing		Deceleration		Acceleration		Coast	
Payload	1,750	1,750	1,750	3,000	200,000	200,000	200,000	200,000	200,000	200,000	200,000
Hulls/Ancillary	1,250	1,250	1,250		10,000	10,000	10,000	10,000	10,000	10,000	0
Asteroid				508,529,370	0		5,758,882				
O2		21,005			189,143,207	141,857,406		1,470,353	1,470,353		
Waste					295,536,261			4,043,471			
H2		3,501			23,642,901	23,642,901		245,059	245,059		
Total	3,000	27,506	3,000	508,532,370	508,532,370	165,710,306	5,968,882	5,968,882	1,925,412	210,000	200,000

TABLE 13-6 LH/LOX OPTION

To consume the required 1715k mt (combined LOX and LH) fuel during the 8 hours we specified for our powered maneuver will require 116 engines. At 3200kg a piece our engines would weigh about 371 mt- a very small part of our mass.

Based on this analysis it seems that the LH/LOX option may be better- and for the powered maneuver at the sun it is- we use only about 2/3 the hydrogen. However, if we look closely at the asteroid redirect portion we can't make this work. The amount of Hydrogen used for the redirect is over 6x more than what we need for NERVA. Our need for a 15kps velocity change of an asteroid requires a very large MR (about 27) and the time and power required to separate this much hydrogen from water is too large. If we assume we dedicate 400MW power supply for hydrogen and oxygen separation, we will create 200mt per day. It would take us 324 years to separate almost 24million mt of hydrogen. Even the NERVA+ redirect would require 52 years. Clearly we will have to start our LH separation process earlier and commit more power to this process. If we use 1GW we would create 500mt of Hydrogen per day and be able to separate the required quantity for the NERVA+ option in 21 years.

A partial solution to this is if we reduced our dV of the asteroid. If we used a Kuiper Belt object or some slower moving body in the outer solar system that required only a dV of 8kps both the Nuclear and LH/LOX solutions become more tenable.

The disadvantages of NERVA+ are that while more mass efficient with fuel, they generate less thrust because of a lower mass flow rate. They are also not part of the rockets launched from Earth... they are part of the payload which means additional flights will be needed to assemble our original four colony ships. Furthermore, they are heavier, will require more engineering development and will face political issues. Counterintuitively, they require a slightly larger hydrogen tank for the sun powered maneuver since they only use hydrogen for mass as opposed to the SSME+ LH/LOX. Unfortunately for us, the desire to move the asteroid with a dV of 15kps will likely trump all the positives of the LH/LOX combination and NERVA+ becomes the more viable option.

Using the numbers shown in Table 13-5 we can see that our asteroids mass originally started out as about 74 million mt. This is huge but for an object with a specific gravity of 2.5 it only works out to an asteroid with a diameter of about 520 meters. Of this 74 million mt mass, assuming water accounts for 40% and the balance of 60% (about 45 million mt) are elements and materials other than water. If the asteroid were only 20% water we would need a larger asteroid, and during our mining operation we would dispose of a greater amount of waste slag. With our 40% water mass, from the non-water 45 million mt balance, we need about 250,000 mt of material to fabricate our torus, mass driver and all the ancillary equipment. Once sufficient materials are obtained to construct our ship, we can dispose of the remaining material as slag. We would prefer to do a majority of this disposal before we do our engine burn to drop our asteroid toward the sun- but it is not necessary. It would require us to do additional burns to get to our 15kps target. We can continue to dispose of some residual mass during the several years we spend dropping toward the sun.

Let us assume we build our Hydrogen tank similar to the way we constructed our torus. Our hydrogen tank will store 372,000mt for the power maneuver. This is a lot of hydrogen. Using our power supply that we discussed earlier in this chapter we would create 500mt of hydrogen per day. This would allow us to fill our LOX and LH tanks in about 744 days which would be done as the asteroid ship drops toward the sun. My proposal would be to construct a 372,000mt tank hydrogen tank that is optimized for the powered maneuver. However, for the asteroid redirect we cumulatively need about 10x more fuel so we would either need to build additional tanks to store this fuel or would go through 10 cycles of fueling and rocket thrust over a 20 year period to move our asteroid.

As mentioned, our hydrogen tank will be very large - 3500x larger than the hydrogen tank on the SS or a 5.253 million m³. This requires a spherical tank 216m in diameter. We need to develop a more accurate method of determining our mass than our rule of thumb of 17.5 kg/m surface area.

Let us assume we have our Hydrogen tank with the following specifications:

Using equation for a calculating stress on a pressurized sphere:

$$\sigma_{sphere} = \frac{p_o R}{2t}$$

If we set $\sigma_{sphere} = \sigma_w = \text{working pressure} = 200\text{mpa}$ and rearrange the equation to calculate for t we get:

$$\text{EQUATION 13-2 } t = \frac{p_o R}{2\sigma_w}$$

$$t = \frac{.2(108)}{2(200)} = .054\text{m} = 54\text{mm}$$

To calculate the mass of a sphere with 54mm thick walls we use the equation for surface area of a sphere:

$$\text{EQUATION 13-3 } \text{Surface Area}_{sphere} = 4\pi R^2$$

Plugging in our radius of 108m in:

$$\text{Surface Area}_{sphere} = 4\pi 108^2 = 146,574\text{m}^2$$

At 2.7mt per m³, with a 54mm thick shell our tank will mass 21,370mt.

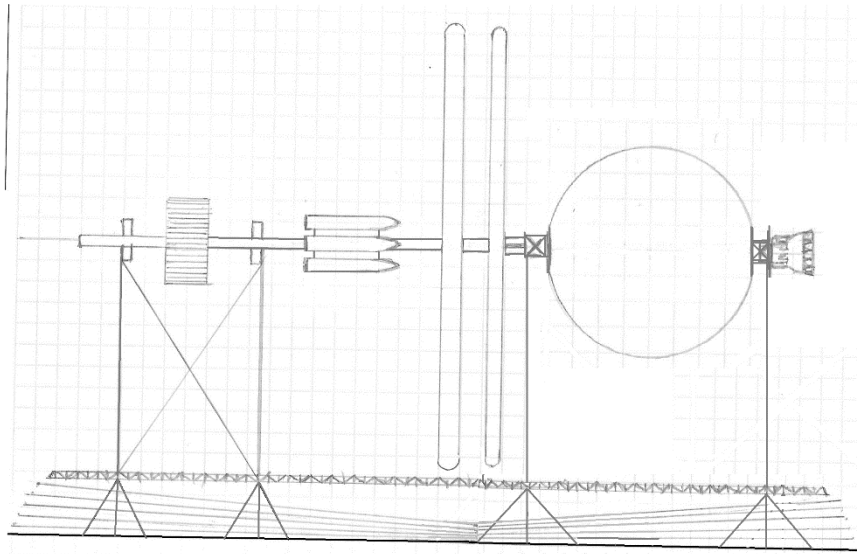


FIGURE 13-7 SATURN C PHASE 3 WITH NERVA+ ENGINE MODULE AND SUNSHIELD

It should also be noted that our tanks will need some reinforcement since this number only calculates the internal pressure stress. However, the working stress used for aluminum, as mentioned before, is conservative. It is likely that whatever aluminum alloy is used will have a higher working stress. Furthermore, our acceleration forces, especially when doing our asteroid redirect, will be very low.

Disposal of unneeded mass

Once we are done with our powered maneuver, we are free to dispose of any unneeded mass. The items that are not needed would be:

- Engines- 860mt
- Sun Shield- 2500mt
- Hydrogen tank- 21,370mt

This implies that we would dispose of about 24,730mt of mass after our maneuver- mostly aluminum from our LH tank. I assumed that not all of this would be disposed of- some of this mass will be kept and recycled for our ship. For this reason, I assumed that only 10,000mt is actually disposed of after the maneuver.

Summary and Conclusions

From four large earth orbit colony ships we set up an asteroid colony and started building our starship. An analysis of the two options (NERVA+ or SSME+) for an aggressive powered maneuver, we determined that to move our asteroid into a highly elliptical orbit with a 3radii perihelion and to do a solar powered maneuver, the NERVA+ combination is better- primarily due to the huge MR and the attendant water separation requirement for the LH/LOX engine. Even with the NERVA+ we would require a precursor colony be set up on our asteroid a decade or more earlier to begin the water electrolysis.

The asteroid, comet or Kuiper Belt object that we select should be water rich... the need for large quantities of oxygen and hydrogen swamps the need for all other raw materials. The Starship and its associated "construction industry" will likely need only about 250,000mt of material (primarily metal, but also various other minerals as well as Uranium). If the asteroid is 40% water and we recover all of it for our starship and asteroid redirect, the total mass of the asteroid would be on the order of 120 million mt. The 40% water mass will be used primarily to create the LH fuel for the asteroid orbit adjustment and powered maneuver around the sun leaving about 45million metric tons of non-water asteroid mass for our ship construction. Of this only about 250,000mt is needed – or around 1/180th of the asteroids total non-water mass- the rest would be thrown away. Even if we selected a comet that was 90% water, there would likely be enough residual metals and ore to build our ship.

Imagine how impressive the powered maneuver would be around our sun? For 8 hours we will have 86 engines putting out 99 MN of thrust, and exhausting 12.9mt of water per second while swinging only 3 solar radii from the sun. I suspect that this manmade object would look like a very bright comet from the earth.

At the end of our powered maneuver, we would eject our unneeded mass and have a 200,000mt ship traveling around 80kps. If we called it quits at this stage our journey time to 10 LY would be about 37,000 years. However, we would need to build up our starship mass (though with our lower speed our total mass to be able to decelerate would need be only 450,000 mt). Since we already require resupply via the MMD we will take advantage of this to further ramp up our speed.

Chapter 14- Phase 4/5: Years 14-721

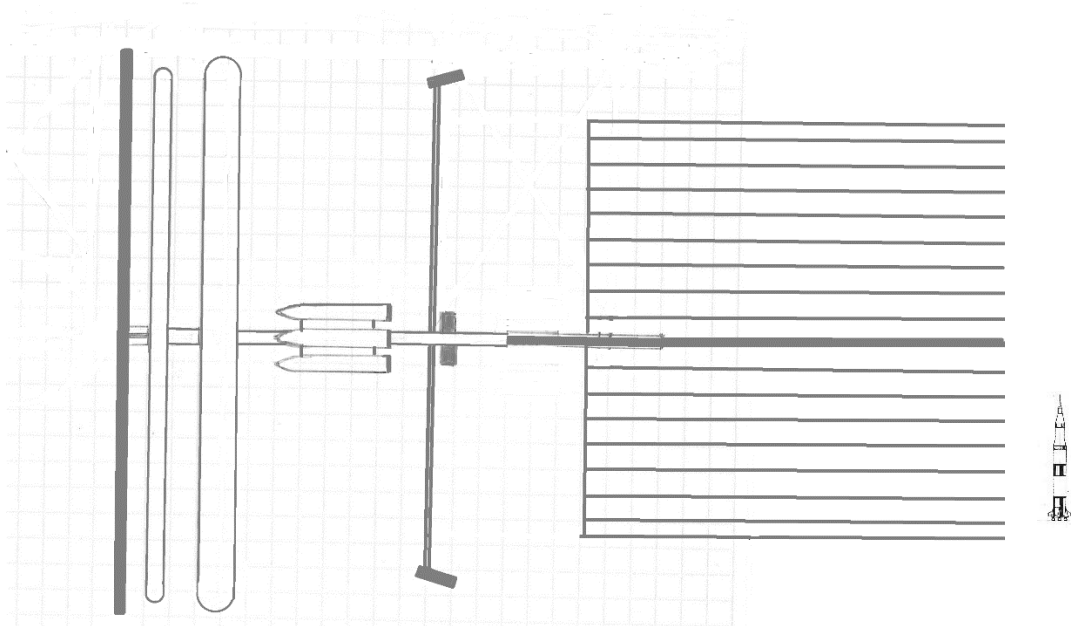


FIGURE 14-1 STARSHIP SATURN C PHASE 4/5 AND SATURN V (TO SCALE)

Phase 4: Years 14-87- Acceleration Phase

In this phase we prepare for the arrival of our packets, commission our power supply and the MD and then increase our velocity from 80kps → 300kps.

Several days or weeks after our powered maneuver we could dispose of our large engine packet and heat shield. Depending on the results of a thorough analysis, and depending on the accuracy of our ship trajectory, we may elect to keep the sunshield for the small amount of extra cosmic ray protection it provides until we are about to begin receiving packets.

Regardless, our starship is now traveling at 80kps toward the target star. At 80kps our starship will travel almost 7 million kilometers per day- or 2.5billion km per year. During this time the ship will be getting into position for the packets that have been launched from the MMD.

Before the packets arrive, we will need to start modifying our spaceship to be ready for receiving the packets and operating our MD. The following needs to be built out- likely during the first year after sun powered maneuver:

- Mass Driver construction. The mass driver components would have been fabricated before the sun diver maneuver since as mentioned before performing our delta V maneuver around the sun with a 50km assembled mass driver would not have been practical or desirable- a heat shield protecting such a long assembly would be very massive. In addition, the acceleration

forces caused by the maneuver would have put excessive stress on a 50km long MD. For this reason, we would preassemble MD sections which we would start being bolted together during this first year of coasting.

- Construction of the radiators for our reactors would occur at the same time. For the same reasons we did not deploy the MD until after the powered maneuver we would not be able to have our radiators deployed until the heat shield is ejected. As discussed, the radiators would be positioned down the spine of the MD and would extend for over 2km. Once the radiators are in place our Nuclear Reactors required for our MD would be available to provide power. One difference is that the radiators likely would be built and deployed while the asteroid processing is occurring since we will need a large reactor to both process raw materials and perform the water electrolysis in preparation for our asteroid redirect. As the asteroid drops toward the sun we would need to disassemble them, and reassemble them after the sun powered maneuver.
- Installation of our packet retrieval system. Depending on the final design, this has probably already been fabricated and would need to be deployed and commissioned.

Meanwhile, as large asteroid (likely in the outer asteroid belt or perhaps even a Kuiper Belt object), would have been used to construct a large MMD. After the powered maneuver it would start firing 20kg packets at a speed of 80.03 kps. Our starship would follow a path as shown in Figure 11-3. Over the next 73 years packets will arrive at our ship at the rate of one packet every 105 seconds. Our mass flow of our starship MD would be .19kg/sec. The starship MD will accelerate 1kg at 10000g for a force of 100,000nt once every approximate 5.25 seconds. We will average 19,000nt of force.

A mass flow of .19kg per second equals 16.4mt per day, arriving on about 820 packets. This works out to 5992mt and 300,000 packets per year. Over the 73 years we are under acceleration we will need 437,500mt of reaction mass delivered by about 21.875 million packets. Our starship will require about 1.2GW of power to propel .19kg per second to an exhaust velocity of 100,000mps plus the power we need for our habitation module.

How will these packets be collected by our starship? Partly this is determined by how accurately we can position them with our MMD. If we feel we can keep them within a few hundred meters of our target location, we may be able to collect them with a series of radial arms (or Catchers Arms) positioned around our spaceship- a longer versions of the Canadarm installed on the SS and ISS. The packets are fairly small and travel relatively slowly. The items would be captured in a basket, then brought down to the processing station on the ship. One packet will arrive every 105 seconds, but because of small inaccuracies in velocity or trajectory the specific packets may be several hundred meters off trajectory and because they will have been coasting for years, some packets will arrive within seconds of each other. Regardless, for redundancy and the need to capture and move the package to the processing facility, we will need to have multiple arms- at least four radially positioned around our centerline.

A more flexible alternative capture method and one that may be able to capture items hundreds or even thousands of meters off target is to launch a capture bucket and net attached with a line. Like the Catchers Arm, four recovery points would be arranged around the spine of the ship. The capture bucket would mass perhaps 50kg and be launched at 30mps by a small mass driver canon. It would consist of a large composite net and be attached to a reel on the ship that would pay out as the capture bucket traveled to the intercept point. The capture net itself would be about 10m wide. Once the packet hit the net the net would close automatically and the capture bucket, net and packet would be reeled quickly

in- the deployment and reel in phase would take (assuming the capture point is about 2km from the retrieval point and the capture bucket travels both ways at 30mps) 66 seconds each way. The buckets would be fired so that they intercepted the packets. The firing driver would have a conic gimbal range of 30degrees, which means that the end of the 2km cone capture area would be one kilometer in diameter. If this is too tight of a capture cone we could either increase the gimbal range (say to 45deg) or launch the capture bucket earlier and let it run for a further distance- perhaps 5 km.

It may seem that the risk of hitting the mass driver would make this whole operation a risky proposition. It is but it should be noted that these packets will not be invisible... the Starship would be able to track them days or weeks in advance and maneuver the ship slightly to ensure the packets avoid impacting the mass driver or radiators. Furthermore, a capture bucket method would have some overlapping cones of coverage and a large range of up to 2km behind each of the four retrieval mechanisms which will keep any packets from getting too close to the main structures of the ship. Also, as several packets may be approaching the same side of the ship at a time, I would foresee the ship slowly rotating so that a second launching arm can be deployed while the first arm is still capturing or reeling in the prior packet. We may also be able to position the capture bucket further down the spine (say 47km) on the other side of our radiators where neither the incoming packets or our capture bucket will accidentally hit them.

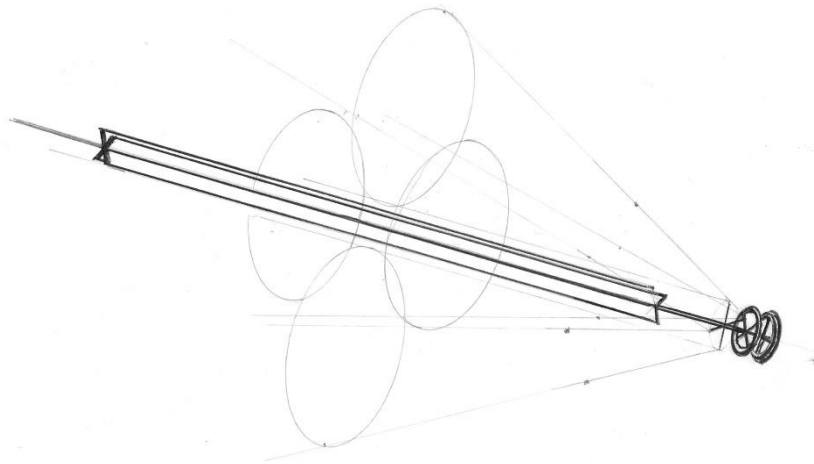


FIGURE 14-2 STARSHIP PACKET COLLECTION CONES (NOT TO SCALE)

However, this would cause flexing of our MD and would have the additional complexity of needing to send the packets and their payloads back up the 46 kilometers too where the payload materials could be separated and the mass launched. Alternatively, the packets can be launched ahead of our ship and our ship would slowly catch up to them. However, this means that the packets will need to be launched earlier in the mission, perhaps before an accurate trajectory is determined. A detailed benefits analysis would need to be performed to determine the best option.

The power requirement during acceleration will peak out at about 1.2GW. Per our nominal reactor specification in Chapter 9, and assuming 50% fuel recovery we will consume 11.5 mt per year. During the 73 years of acceleration, this equates to about 840mt of fresh 5% enriched fuel.

After this acceleration period ends our power demands will drop considerably- to about 15MW. This means our fuel usage will be considerably less... requiring only .1725mt per year. This works out to about 17.25mt per century.

Phase 5- Years 87-721 Expansion and Build Out

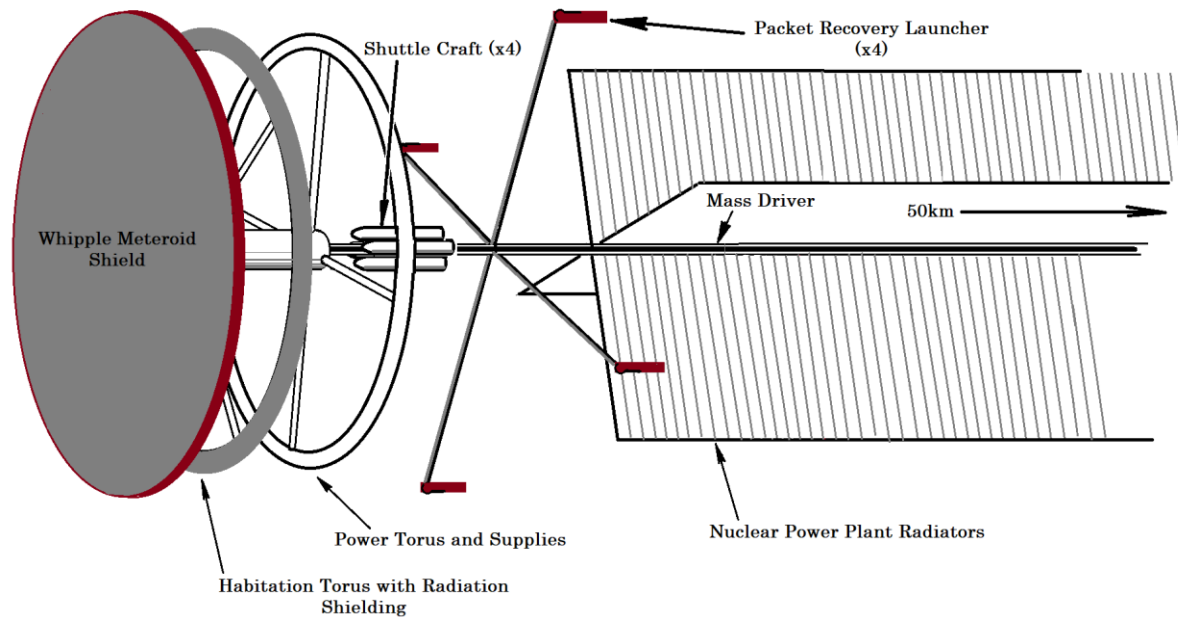


FIGURE 14-3 COMPLETED SATURN C STARSHIP

Once we complete our acceleration phase the packets will continue to arrive once every 105 seconds. We will accumulate mass at the rate of 5992mt per year for the next 634 years. Initially most of the arriving material will be water to be used for our cosmic ray protection. To build up to our required 550,000mt from our starting point of 85,000mt will take 78 years- but our actual payload of water would only represent 50% of the mass which means the water will take 158 years to accumulate. All is not lost however as even the metal/plastic that make up the bucket and electronics can help with radiation protection. In addition, we will be building our meteoroid bumper which can also serve as radiation protection. For some of the packets, instead of water, a few would contain ^{235}U to replace the spent uranium.

Our final m_0 target mass required to reduce from 300kps to 0kps with an I_{sp} of 10,000 and a m_1 of 200,000mt. This requires a MR of 20 and means our spacecraft will eventually peak at 4million mt and will take 634 more years of mass accumulation from about 190million packets.

During the expansion and construction phase we will- in the following priority

- Improve our radiation protection.
- Expand our colonizing equipment and supplies.
- Accumulate reaction mass for deceleration.
- Build a meteoroid shield.

The 10kg payload of each 20kg packet will be considered during the detailed planning process. Scattered through the deliveries will be several items as noted below (Chapter 16 will go into a more detailed breakdown):

- Water- to expand our radiation protection to our target of 6m. In addition, this will replace water, hydrogen and oxygen lost through attrition.

- Uranium (or Thorium) to replenish our power supply
- Nitrogen- small quantities to replace what is lost over time.
- Miscellaneous trace materials
- Bulk materials that will be used for reaction mass on deceleration. This will mostly be water.

Plastics and other trace elements will likely be delivered as part of the bucket mass.

The solar system MMD that will be projecting our 20kg payloads for both the initial acceleration phase as well as the build out phase and will have to maintain a very high rate of fire- that will need to increase as our starship speed reaches 300kps. We assume that our approach speed to our Starship is a maximum of 30mps- this works out to .03kps. Our ship is traveling at 300kps so that the approach speed will be only 1/10,000 of our cruise speed. This means that the solar system based Mega Mass Driver will need to launch 10,000x the rate at which they are receiving mass. We are receiving packets at 34 an hour- or one every 105 seconds. This means at our starship peak speed of 300kps our MMD will be sending out packets at the rate of 95 per second, each massing 20kg- for a total launch mass flow rate of 1900kg per second. It also means that the MMD will only need to operate for about 24 days for the entire Phase 4 part of our mission.

For acceleration we determined we will need 21,875,000 packets. These will be launched at a gradually increasing rate as the starship slowly accelerates. At the beginning when our starship is traveling at 80kps we will be launching our packets at 80,030kps at the rate of about 25.4 packets per second. Gradually we will increase to 95 per second.

Following the acceleration portion of the voyage we will need to provide 3.8million MT of mass to build out our ship and accumulate our reaction mass for deceleration. This requires 190 million additional packets.

	MT	Notes
Torus (2)	38,000	Habitation Torus and Power/Industry Torus
Power Source	52,000	59000mt total: 750mt for crew torus; 59,400mt for mass driver, minus 8000mt carried in second torus
Radiation Shielding	85,000	
Propulsion System	25,000	50km mass driver; 10000sec Specific Impulse
Colonizing Supplies	4,000	
Total m1	200,000	
Phase 4/5 Shielding	465,000	Primarily Water Ice. Brings total mass of Shielding to 550,000mt (465,000mt will eventually be used for reaction mass in Phase 7)
Additional Equipment During Cruise	20,000	Because we have additional reaction mass that will be unused until deceleration, this mass will be to provide additional mass for equipment and replacement of spent uranium etc.
Reaction Mass for Deceleration	3,315,000	The additional mass will also serve as meteoroid and cosmic ray shielding

m0	4,000,000	Mass ratio of 20 required for deceleration

TABLE 14-1 MO STARSHIP MASS BREAKDOWN

The number of packets required may appear to be unrealistic- for acceleration and ship expansion we will need a total of about 215million packets. However, except for their “payload” the bucket and electronics are identical. Apple’s Tim Cook stated that Apple had made 500million iPads from 2010 to 2020 so mass production techniques would be up to the task.

A bigger problem is that to launch 1900kg per second at 300kps will require a lot of power. Our Kinetic Energy formula says we need 85.5TJ. This is greater than the current electric generation of the Earth. Indeed, our Starship, with an Isp of 10,000 and ejecting only .19kg/s will use 950MJ or only 1/90,000 as much power. Using our 20W/kg we come up to a reactor mass for our MMD of 4.276 billion tons (4.276×10^9)!!!

We can only reduce the size of the MMD power supply a couple of ways. If we can reduce our Starships top speed to 200kps and then our peak power requirements would be less than half. Assuming we keep our approach velocity of 30kps our total velocity will now be 200.03 and our peak rate of fire will also be less... 63.5 per second, and our mass 1270kg/sec. Our energy required will now be 25.4TJ. Still substantial.

The easiest way to reduce our peak energy requirements is to increase our packet approach velocity. If we increase from 30mps to 60mps, we will reduce our MMD launch rate in half- or to only 42.5 packets per second. This will not change the total TWh needed, but instead of all our packets being launched in a little less than a month, they will now be launched over almost two months and our peak power requirements will be only half, or about 43TJ.

This may be an unreasonable amount of power- but unfortunately this is the kind of power needed for a starship mission. If we can’t create TW’s of power on the MMD Asteroid, Starship travel will not be possible. In Chapter 16 we will look at how to generate (and store) this amount of power.

With our 200,000 mt ship, and our 550,000 mt cosmic ray protection in place, a majority of our remaining mass will be placed in front of our ship for meteoroid protection and for storage of reaction mass. What would be the nature of our meteoroid protection?

Whipple Shield

Our starship’s torus diameter is about 402m but our radiator wings are nearly 200m each wide on each side for a total of 400m. Ideally we would want our meteoroid shielding to be slightly larger to protect our vehicle. If we were to have a shield disc of 420m we would have a circular area of 138,544 m.

Even though impact with any object larger than dust will be infrequent, building of a shield would be prudent. A .1kg object traveling at 300,000mps has tremendous energy- 4.5×10^9 joules. This problem has been looked at before and effective mitigating strategies are available and have been developed. In 1947 F.L. Whipple proposed what has since been named a Whipple shield whereby a thin bumper of metal offset from the spacecraft can protect the underlying spacecraft (Whipple, 1947). When a meteoroid impacts the outer bumper, it and a portion of the bumper vaporizes and dissipates its energy

before significantly impacting the underlying spacecraft. Since this original work, various versions of Whipple Shields have been used on spacecraft, including Skylab, Apollo and the ISS. Many iterations can be considered including a single bumper, or multiple bumpers at various standoff distances. The type of shielding used is determined by the expected environment (velocity, number/frequency, size, and make up of meteoroids), the shielding material available, and the shielding mass requirements. In most cases to date, the mass of the spacecraft is critical and the lightest effective shield is used. The ISS has various types of shielding mounted depending on the perceived risk as well as national preferences. NASA's



FIGURE 14-4 WHIPPLE SHIELD

version is different than the one used on the Japanese module which is different than that used on the European modules.

A typical enhanced version of meteoroid protections is the Nextel/Kevlar Enhanced Whipple for the International Space Station which has three layers and can block up to 1.35cm aluminum impactor traveling at 7kps (Christiansen, 2003). In this version, an outer layer of 2cm thick aluminum is positioned in front of a 12-layer blanket of alternating Nextel and Kevlar followed by the .48cm aluminum shield. The first layer is about 11.4cm offset from the spacecraft hull. In the case of our Starship, our impinging

meteoroids will be traveling some 40x faster and will have energies over 1800 x greater. However, the ISS is in low earth orbit where impacts are many orders of magnitude more common than in interstellar space. Furthermore, we will have many meters of material between our bumper and our ship so some version of a Whipple Shield will be effective- possibly several layers of aluminum plate or mesh each several meters apart. A greater standoff distance leads to a wider vapor cone, and greater dissipation of energy before impinging on the next layer which is required to handle the tremendous speeds involved. Below these multiple layers we would have many meters of mixed material. If we used this shield to store all our reaction mass for deceleration and had a SG of 1.5 (a large percentage would be water) the bottom shield could be 18.3m thick (assuming a disk shield of 420m in diameter)- enough to serve as a very effective shield.

Supplies

Supplies are the resources the colonists originally took, as well as those delivered via packets. A perfectly closed system is impossible but for many of the materials, especially those stored as solids, losses will be insignificant. For some materials, particularly volatiles, there will be substantial losses over thousands of years. Let us look at all of our raw materials required to survive our journey.

Uranium swap outs will be a large issue. As noted previously, if our steady state power usage during Phase 5 and 6 is 15MW we will go through 17.25 metric tons of enriched Uranium every century (assuming that we can reprocess at 50% efficiency). For Phase 5-6 of our mission will last on the order of 9000 years. At this rate we will need **1,553mt** of fresh enriched U during the cruise phase. During Phase 7, we have 634 years of deceleration, where we will need 1.2GW of power. Again, assuming about 50% recycling we will need about 11.5mt of fuel of fresh enriched fuel per year or about **7300mt** of fuel during the deceleration period. If we bring all the needed fuel for the acceleration phase on our mission

start, we will then just need to provide the fuel for cruise and deceleration. For Phase 2 expansion and build out to phase 7, deceleration we will need a total of about 8,850mt of enriched Uranium.

Except for Uranium, which is burned up (consumed), and some volatiles which will invariably leak, most of the rest of the raw materials should be recycled.

Recycling

The supplies needed depend in large part on how effective our recycling is. Near 100% recycling will be possible and necessary for many items. The fact that our starship mass is 4million mt means that a large reservoir of supplies would be available to address imperfect recovery.

Loss of volatiles are likely to be the area of greatest material loss and therefore of most concern. If we lose the Nitrogen and Oxygen atmospheres in our torii at the rate of one atmosphere every 100 years, we will need 100 complete changeouts during our 10,000 year mission. We calculated that one 15m torus has 230mt of atmosphere. Adding in the mass for our hub and some additional atmosphere for the second torus we can round up and assume a total of 500mt of atmosphere for our Starship. Because I reduced our atmospheric pressure to 80% of SL, I also bumped up the Oxygen Content from the normal 21% to 25%. By mass the Nitrogen/Oxygen ratio would be by about 72% Nitrogen to 28% Oxygen. Over our 10,000-year journey we will go through 50,000mt of Atmosphere. Of this about 36,000mt would be Nitrogen which will have to be delivered via packet- likely as ammonia where Nitrogen is about 82% of the mass. We will therefor need about 44,000mt of ammonia.

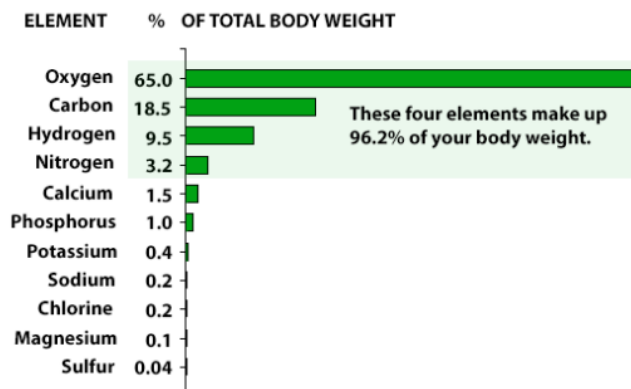
Oxygen would be derived from Water also delivered- both for our Cosmic Ray Shielding but also to replace Oxygen that which was lost.

We may also assume that our reactor cooling radiators will occasionally leak. The radiators will have thousands of kilometers of piping. My initial assumption is that this cooling fluid will be water but other liquids, including ammonia, may be candidates. Regardless, some of our cooling fluid will be lost over the centuries and need to be replaced.

Most Noble gases, including Helium, Argon, Xenon, and Neon can be kept in small quantities for some manufacturing and welding requirements, with a few tons total being enough. These may also be lost over time, but the quantities required are quite small and the supplies at the beginning of our voyage may last for the duration.

The ship is built of aluminum (or some other metal) and since Aluminum is part of the original structure and does not wear out, not much more will be required during the cruise. Nevertheless Aluminum, along with other materials such as Iron, Nickel, and titanium may be either stored originally or delivered enroute to aid in building and expanding the habitat or replacing worn out components. Some, if not most of these metals are part of our MMD bucket, including the electronics, so may not even need to be delivered as the packet payload.

Living organisms have many elements in small quantities but Oxygen, Carbon, Hydrogen and Nitrogen make up over 96% of your mass. One sensitive area that would need to be addressed is what to do with the people who die on the voyage? On average, assuming a lifespan of 85 years, almost 12 people will die a year. If someone dies at sea, they historically were buried there (though no longer easy to arrange- it is considered pollution and is rigidly regulated by the EPA). Releasing 12 personnel (average 82kg each) at a cumulative mass of 980kg per year, will add up to 9,800mt over the course of 10,000 years- none of which will be recycled unless we do an alternative recovery method. The loss of water and oxygen should not be an issue, but human bones and other organs have critical minerals that may be more important to be recycled- including phosphorus and potassium. The decision will have to be made as to whether we need these elements and if so, how do we recover them? To avoid a Soylent Green type scenario, while still recycling, a compromise may be cremation whereby the ashes are used for the growing of crops. The corpses' water would also be released during the cremation process.



The eleven common elements found in the human body and their percentage of total body weight. The other trace elements (less than 0.01%) are: boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).

FIGURE 14-5 ELEMENTS IN THE HUMAN BODY

If humans are not recycled the following elements would be lost over the duration of the mission:

Element	Element as % of total body mass	Loss over 10.000 years
Oxygen	65%	6,370mt
Carbon	18.5%	1813mt
Hydrogen	10%	980mt
Nitrogen	3.2%	314mt
Calcium	1.5%	147mt
Phosphorus	1%	98mt
Trace	.8%	Potassium, Sulfur, Sodium, Chlorine, Magnesium

TABLE 14-2 ELEMENTS LOST DUE TO IN SPACE BURIAL

Compared to other materials these quantities are fairly low. For now, I will assume two scenarios- 99% recovery of human remains and 0% (bodies will be buried in space). Both scenarios also assume 100 atmospheric changeouts for the duration of the mission to account for inevitable leakage. I assume that the original "soil" will contain all the required elements to support plants and animals. I also assumed

some original supplies are provided at mission start- in particular water (for cleaning, watering crops, cooling of atomic radiators etc.) as well as ammonia.

Initial Supplies	Original Supply (mt)	Resupply with no recovery	Resupply with 99% recovery	Comments
Water	1,000	22,916 (33,000mt)	15,817 (26,000mt)	Water resupply will be used to replace lost Oxygen (10,000mt added to address Coolant leakage)
Oxygen	265.3	20,370	14,060	Derived from water; Oxygen atmosphere loss
Hydrogen	NA	980	10	Unneeded hydrogen can be disposed
Ammonia	100	44,285	44,003	Used to replace lost Nitrogen
Nitrogen	235.3	36,314	36,003	Nitrogen atmosphere loss, Fertilizer
Hydrogen	NA	NA	NA	Disposed
Carbon	10	1.8	.18	Life; primarily taken up by plants from atmospheric CO ₂
Calcium	1	1.47	.15	Life
Phosphorus	1	.98	.01	Life
Miscellaneous Trace elements for Life	1	.8	.008	Potassium, Sulfur, Sodium, Chlorine, Magnesium
Miscellaneous for Manufacturing	10	10	10	Small quantities of metals/alloys
Uranium Enriched Ore	100	10,000	10,000	Original Supply of Uranium for Phase 2-3

TABLE 14-3 REPLACEMENT QUANTITIES IN MT

Finally, in calculating our Uranium requirements we assumed that we would reprocess spent Uranium at the rate of 50%. If we are not able to reprocess then the Uranium required would be twice that suggested.

Miscellaneous Elements for manufacturing include metals but also silicon. This is a place holder but since most metals and silicon could be recycled, not much would be needed for resupply.

Summary and Conclusions

This analysis shows that a majority of the needed supplies will be Water, Ammonia, and Uranium, in that order. The Nitrogen and Oxygen will be replaced via Ammonia (about 44,000mt) and Water (about 23,000mt) respectively assuming human bodies are not recovered.

If the colonists opt for deep space burial, disposal of bodies in space can be done with minimal additional resupply- primarily requiring a total of 5 metric tons of mostly Carbon, Calcium and Phosphorus.

Some coolant leakage is also assumed so an additional 10,000mt of water is added.

During our resupply 10,000mt of enriched Uranium will be delivered. If it were supplied as unenriched Uranium then the total quantity required would be on the order of 100,000mt. Sticking with enriched Uranium, the total mass delivered between water, ammonia and Uranium would be about 87,000mt. The assumption is that the water and ammonia are lost or consumed. The spent Uranium can be used as reaction mass.

In addition, for our cosmic ray protection we would need another 465,000mt of water.

All other resupplied materials would only be less than 15 mt- including those trace materials required for life, as well as silicon and metals for manufacturing. This brings our total required supplies to about 557,000mt. To decelerate our ship we required 3,800,000 of reaction mass so our required supplies are only a portion of what needs to be delivered. The balance would likely be the unneeded mass from the bucket as well as extra water- both of which could be used for a meteoroid Whipple shield.

Chapter 15- Years 722-10,000- Phase 6/7/8 Cruise, Deceleration and Colonization

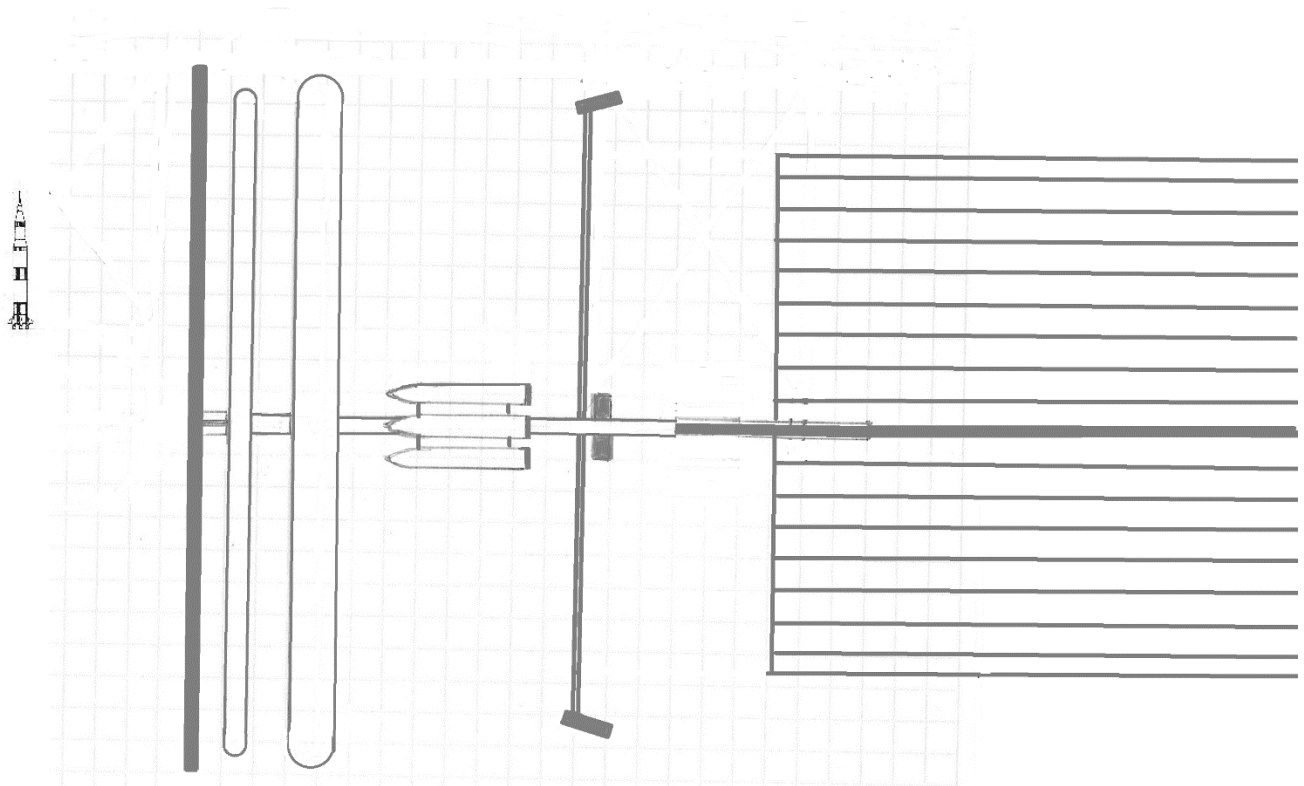


FIGURE 15-1 STARSHIP PHASE 6/7 AND SATURN V (TO SCALE)

The bulk of this book is dedicated to the engineering challenges of building and launching a Starship. However, from a mission point of view the vast majority of the time, the starship will just be cruising with the colonists sequestered aboard a 4 million mt ship of very finite dimensions and limited resources. In this chapter we will both discuss engineering as well as the social challenges of a 10,000-year voyage.

Humans have lived in small, isolated communities before. It is believed that the 4.6km Pitcairn Island (eventual home of the mutineers from the HMS Bounty) had a small population for a couple of centuries. However, they likely had some limited interaction with other islands for trade- primarily Henderson Island. The scope and audacity of our small starship colony is to some extent without precedent and the challenges will be substantial.

Phase 6- Cruise- Years 722-9000

The voyage will be long. What are the issues and challenges the colonists will face during their 10-millennium mission?

During the cruise phase our starship will be traveling at .01% of the speed of light- or one light year per thousand years. As has been repeatedly emphasized during this book, this seemingly modest velocity was tremendously difficult to achieve... requiring many terawatts of power. Nevertheless, it is probably the most we can hope for with 21st century technology.

At these speeds, the cosmic ray risks will not be substantially different from a ship just floating in interstellar space. Impacting interstellar gas or dust should not be much of an issue either. The impact of large particles may be an issue but are relatively rare. Both are handled in our design.

Manufacturing and Fabrication

The colonists will have many challenges during the 10,000-year voyage. The basic physical structure of the ship (the tori, the MD spine) will last the life of the voyage. Some limited patching of the hull may be needed if for some reason it is punctured. However, other items onboard the ship will wear out and break and some level of repair capabilities will need to be onboard our ship. Some examples to consider:

Sheet metal:

Making sheets to either modify, expand, or repair our structure. Bending and wire drawing will be needed. Manufacture of millions of buckets will be required for our MD. It is possible that the packets delivered by the MMD can be designed such that they are modular and can be disassembled and quickly turned around into a smaller bucket with minimal manufacturing.

Foundry:

Some sort of foundry will be required where liquid metal can be poured into forms.

Manufacture of pipe:

Long lengths of pipe will need to be manufactured for plumbing, cooling of reactors, recovery of sewage and distributing fresh water. Various diameters from thin tubing to piping perhaps a meter across may be needed. The power reactors and their associated cooling radiators are huge and will need a lot of piping manufactured during Phase 2-5, but additional piping will need to be made to replace worn or damaged parts.

Machined Parts:

Mechanical parts like pumps and turbines. This will require the ability to cut, bend, or form metal, and plastic tubing. Machine lathes, drills, presses, and saws will be required.

Manufacture of Rubber and Composites:

Mechanical parts like pumps and turbines, as well as hatch seals and space suits will require us to manufacture rubber, composites, and plastics. Everything from O-ring seals to gaskets will need to be fabricated. One of the base components for all these materials is carbon so sufficient carbon will need to be brought along not only to provide CO₂ for plant growth but for the manufacturing of these components.

Lighting:

Lighting will be needed continuously to provide the illumination required for the plants and living space. In general, general torus lighting will be on 50% of the time to mirror the day night cycle. This equates to a little more than 4000 hours per light per year. LEDs are tremendously reliable and depending on their installation and design they can last anywhere from 10,000-100,000 hours on average. This implies that most of the LEDs will need to be replaced every decade or so. On a 10,000-year voyage, every LED will be replaced 1000x- requiring the manufacture (and recycling) of perhaps a billion LEDs.

Computer components and electronics:

Advanced manufacturing equipment for the replacement of electronics including processors, circuit boards and memory chips will need to be available. High grade silicon and advanced X-ray lithography equipment will be needed.

Complicated Machine and Robot Repair:

Even though this is a manned mission, robots will be needed. Repairs or construction outside the ship's radiation shield will be relatively dangerous and must be kept to a minimum. The construction of major portions of our ship including the construction and installation of Whipple shielding, Cosmic Ray shielding and our nuclear power plants and their associated radiators will mostly be done via robots.

One positive is that most of the raw materials will have been provided by the MMD packets. Large scale separating and processing of materials will not be needed.

Food Production

This is an area of ongoing technological improvement with the potential for considerable gains in efficiency. Our ship was designed assuming that 5 acres of land would be sufficient to feed 1000 colonists- this is about twice the efficiency planned for in the Space Settlement Study. Over the next several decades, assuming we start building colonies on the Moon and Mars, we will gain a lot of knowledge and insight in this field. For now, we have assumed that we have enough land on our starship to grow a healthy mix of plants, fish and small animals. What animals we bring along will need to have considerable thought. Progress on growing artificial meat may mean that all "meat" will be artificially created and there will be no need for animals- though we may still want other items from animals like milk or eggs. With that being said, if we colonize and create large human colonies on distant stars, even

if there were no requirement for animals, the colonists would likely want to bring along various animals for several reasons. I would think that the following would be considered for our Starship:

- Certain beneficial insects, including worms and bees.
- Cats and Dogs. Humans have a long history with certain domesticated animals and would likely be very welcome in the future.
- Small animals to include Rabbits and birds
- Egg laying animals such as chickens
- Goats for milk

If the technology exists, frozen eggs and sperm should be preserved until the animal is needed and the animal can then be grown in an artificial womb (see Chapter 17). This capability does not exist yet but by the time of our voyage it may. This will permit populating alien solar systems with hundreds if not thousands of different animals. The same applies for fish and plants. In the case of plants, many different types of seeds would like be carried with our colony.

The Human Factors

Considerable thought will have to be made as to how the colony ship will be managed. In the past, there have been isolated human populations that have survived on remote islands for many generations. Some of these isolated communities do become extinct- something that we need to avoid if possible!

The original colonists are likely to be committed and intelligent- they would have volunteered for the mission and likely would have had to pass some sort of psychological and intelligence screening process to participate on this voyage. They would have needed to show a great degree of mental toughness and stability. However, their children and grandchildren would not have gone through this filtering process. They will NOT be volunteers and will not be screened. Genetic diversity is real and even though intelligence and emotional characteristics are somewhat inherited, the tie is weak. If the original colonists were in the top 10% of the human population, the next generation will be still elevated but closer to the normal human mean. In short, three key points will need to be understood:

- The average intelligence of the colonists, if left to their own devices, will decrease after the first generation, and will likely continue to decrease (if left to random behavior) at a slower rate until it approaches the normal human mean.
- Conversely, because of the colonists screening, mental issues will be very rare on the original colonists but, as with intelligence, mental illness will increase with each generation, and eventually approach the normal human rate.
- The highly motivated “volunteers” of the first generation will be replaced by their “non-volunteer” descendants. We see this play out in American society where newer immigrants for the first one or two generations frequently outperform their fellow Americans, until their children and grandchildren become closer to the mean.

These are profoundly difficult problems to address. What happens if someone is a psychopath? What will you do with him/her? How will this sort of issue be identified and corrected before something bad happens?

Studies will need to be made on how best to set up and organize the colonists. These discussions are outside of the scope of this book. However, I did want to touch on the issues and likely solutions as they will demonstrate that not only are the technical problems of traveling to the stars substantial, but the social problems are equally challenging.

While we have some precedents of small, isolated groups of individuals separated from the wider world- but even though they bear some similarities, nothing can compare to the 10,000-year voyage that we are considering. The good news is that before we begin our starship voyage, we should have additional experience with small, isolated settlements on the Moon and Mars. Regardless, our voyage will be orders of magnitude longer as well as far more isolated- all our colonists are committing themselves and their descendants to a one-way voyage.

With that being said, I believe this is an area that can be overcome. The reality is that when survival is at stake, humans usually figure things out rather quickly and will tend to make good decisions. This could be an area where we can be overly concerned and try to eliminate all risks- or “paralysis by analysis”. The reality is that the colonists will need to address issues as they arise- and since their survival may be at stake, they will have tremendous motivation to make good decisions and to be proactive.

Living in a torus

Living in a torus is likely to be very pleasant though, if appropriate activities are not available, extremely boring. If the starship is well designed, then there should not be many emergencies during the 10,000-year voyage. However, the old sage is probably true- an idle mind is the devil’s workshop. People will need to be kept busy and engaged. Mood altering drugs, whether alcohol or some other drug, will be closely monitored and regulated if tolerated at all. Many dangerous industries on earth already operate this way- with random drug tests and essentially zero tolerance for alcohol or drugs. Some examples are the military, pipeline industry, air traffic control, pilots, train operators, nuclear reactor operators etc.

Torus living is likely to be very regimented and monitored. Privacy will be sacrificed to a large extent. The limitations of such a small ship are many but to name a few:

- Work careers will be limited. Much of this is determined by the robustness of the design- if the equipment is reliable and easy to maintain not many individuals will be needed. Flexibility will probably be required of all crew members because you may normally work at a low priority job but have to pitch in when a problem occurs.
- What will the colonists do for entertainment or distractions?
- Population Control. The number of children will have to be regulated. How will this be done?
- Criminals. Criminal activity will be low... there will not be much privacy and on such a small colony, the need to steal will be nonexistent. However mental issues and crimes of passion will occur. What happens when someone gets killed by a jealous spouse in a fit of rage? Will such a small colony have a prison? If someone has mental issues that can be treated with drugs, will they be forced to take “their medicine?” Will there be a death penalty? Many antisocial behaviors on earth are tolerated because modern society has the wealth and stability to put up with it. This will not be possible on a small ship.
- Privacy- there won’t be much.

What will they Do? Work and Train!

We have already talked about manufacturing, recycling, and food production- all will require trained personnel to perform or monitor. The highest priority jobs would those be responsible for maintaining the safety and comfort of the starship. Hull repairs should be infrequent and would primarily consist of a metal patch welded over the skin. More common would be pumps failing or LED lights needing to be replaced. Some of the maintenance tasks and their jobs that will be needed on an ongoing basis:

- Power plant repairs and fuel swap outs. Repairs are of all types including to turbines, cooling, and circulating systems etc.
- Farming. Primarily crops but possibly raising and harvesting small animals like chickens, rabbits, and fish. Also, it is possible that artificial meat will be grown and this will require oversight.
- Motor and pump rebuilding- motors will be used for various pumps around the facility including ones that pump the water used to keep the torus balanced as well as cooling for the reactors. Both the impellers, gears and windings may need to be repaired on motors and pumps. Pumps will need periodic seal replacement or repair. There will likely be automated farm equipment that may have actuators along with motors.
- Vehicle repair- related to farming, there are likely to be automated equipment and vehicles that are used to grow the crops that will have motors and perhaps actuators.
- Sewer system, water distribution and recycling equipment repairs.
 - o Plumbing and pipe repairs in general. There are kilometers of pipes and pumps for water and waste as well as balance of the torus and cooling of the reactors.
- Manufacturing of replacement items. These include
 - o Lights. There will need to be the ability to manufacture LEDs in large quantities.
 - o Circuits/Computer chips- related to LEDs there will be the need to manufacture various types of computer processing and memory chips and circuit boards.
 - o Battery manufacturing. Primarily for the farm equipment as well as for small scale things like flashlights.
- Machining, including metal and composite gears and mechanical parts. Raw material and various metal working equipment like laths, drills, presses etc. A small machine shop will be needed.
- Computer, electronics and electrical repairs.
- Continuous Training- everyone will likely need to be able to do multiple jobs requiring constant training.

What will they do? Entertainment

We can imagine sports like track and field as well as bowling- though the alley will curve disconcertingly upward. More difficult to manage but possible are modified versions of “vertical sports” like baseball, basketball, football, and soccer. Our 15m diameter hull is narrow, and our low ceiling (based on our current design never more than 8.5m above the floor) prevents balls from going very high. In addition, the Coriolis effect will make balls change direction in predictable but inconvenient ways during flight. Nevertheless, the colonists will likely be able to play many sports with appropriate modifications.

It is also reasonable to assume that computer simulations will continue to advance so that many people can participate in virtual worlds. Likely some parts of the ship will have simulated environments that project landscapes and vistas on the walls that give the impression of vast open spaces.

We can imagine plays, musicals and various visual arts thriving- though the small size of the colony would mean the plays and music would have more in common with a local theater than Broadway.

Population Control

We have two population related challenges that will need to be addressed. Our population can either be below our target or above. How do we ensure we stay within what is a fairly narrow range? The simplest and probably easiest solution is to have all babies born artificially from frozen embryo's and in an artificial womb. Barring the technological and sociological issues with this idea the next best is to have a two-child policy, with exceptions for a third child if some mothers are unable to have two. Indeed, this process can be flexible and adjusted for changing conditions. However, it does require a degree of compliance normally not found in free countries. This will have to be one of the many sacrifices that will need to be made by the colonists.

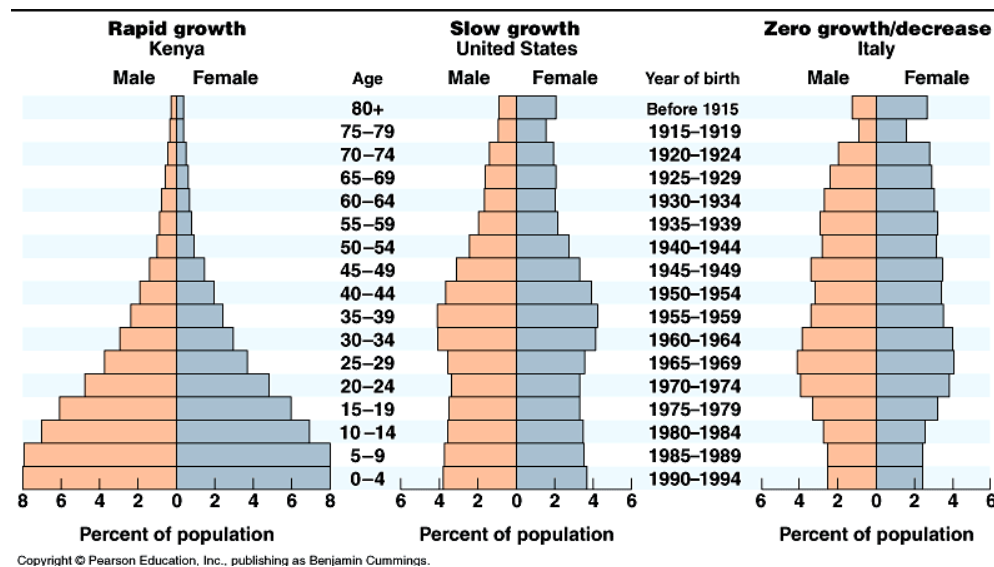


FIGURE 15-2 POPULATION PROFILES FOR RAPID, SLOW AND ZERO GROWTH POPULATIONS

off surprise or resentment. Note that in general the population profile of our starship should mirror that of a zero-growth scenario.

Criminals- How will problem individuals be handled?

Criminal activity will likely be low... partly because of the lack of privacy. The nature of the closed starship society is such that the motivation for stealing would be low. How would you be able to keep a stolen good a secret? Who would you fence your goods to? Besides, the ever presence security cameras, everyone has the same stuff required for comfort- what would you steal? In addition, everyone will know each other, and disturbing behavior will be identified and acted on quickly.

But what happens if a mother gets pregnant and it is not authorized? Unfortunately, many aspects of the colony ship will mirror a military or communist organization, with their attended lack of freedom. If the rules are established and the reasons spelled out ahead of time it will hopefully head

However, we will have some crime- either those of passion, or those caused by some emotional/mental issue. Treatment in the form of therapy and drugs can help but what happens if it doesn't, or the person refuses to take his medicine? What happens if a person is seriously emotionally disturbed? In the case of a starship that can be destroyed by a single, psychotic individual, and with limited ability to imprison them, there may be the need to be the death penalty. How this would be decided on and carried out may best be left to the colonists. It is unlikely that we can determine the right corrective actions for unique incidents that may happen 10,000 years from now. Nevertheless, it is a certainty that these sorts of issues will need to be addressed by the colonists.

Privacy

One mitigating factor in criminal activity is the total lack of privacy. It is likely that all public spaces will be closely monitored for engineering purposes. The only private space you would likely have is your apartment, and even here, there is likely to be passive monitoring... picture an Amazon Echo equivalent!

The lack of Privacy means that premeditated and even some spontaneous criminal activity will be deterred. The reality is that in most stable living environments with a lot of social cohesion, without drugs and other addictions, criminal activity is normally extremely low. There is always the risk of a crime of passion but the fact that everyone knows everyone and sees everyone every day, any brewing problems should be addressed before they get out of control.

Phase 7- Deceleration- Years 9000-9634

Our mass driver will require 3,800,000mt of reaction mass for deceleration. Keeping our 5992 mt per year ejection rate our mass driver will be in operation for 634 years in deceleration. Eventually we will have to start dismantling some of the radiation shield to keep in line with the 200,000mt arrival mass. For about 85% of the deceleration time we have sufficient mass to keep all our radiation shielding in place. Only in the last 95 or so years will we start having to dismantle our radiation protection.

One item that would need to be addressed when preparing for deceleration is that the rocket will have to reverse direction and face backwards. For this reason it would be prudent to move our Whipple Shield to the back of the ship, closer to the end of the mass driver. This requirement will have to be considered when designing our ship and is a task that should be done during phase 6.

Phase 8- Colonizing- Years 9634-?

The interstellar spaceship, on arriving at its target star will need to establish a colony. The nature of this colony will depend on the planets and minor bodies available in our new home. Regardless the raw materials available will be substantial. It is for this reason that we will not need to bring a lot of the colonizing resources with us.... the intent will be to live off the land.

Whatever the star system we enter, the first target(s) will likely be smaller bodies similar to the asteroids or smaller planets without high gravity or a thick atmosphere. The starship would probably

dock with a suitable asteroid and resupply itself with raw materials. However, we don't want to restrict ourselves to these bodies indefinitely. Given the small crew size, it will take many decades before advanced and additional landing ships could be constructed. For this reason, we will use our Earth launched four landing craft (the original hull #7) with little or no modifications.

Landing craft

The capabilities of a Landing Craft is difficult to determine as we don't know what we will be designing for. Are the planets all small without an atmosphere or are they larger rocky worlds with high gravity atmospheres, or any combination in between?

Barring any knowledge of the alien solar system, a good baseline landing ship would be similar in performance to the SpaceX Starship but with some improvements and modifications.

First thing is to settle on the fuel we will use. The two most popular fuels are Hydrogen and Methane. We have a lot of experience using and handling both. Some other common fuels are derived from petroleum products and will be difficult to synthesize. There are very sound engineering reasons why both methane and hydrogen are becoming the fuel of choice for new rockets.

Both fuels have advantages and disadvantages. Further analysis can be done to determine which is better. However, to summarize

Methane (advantages):

- Can be generated from CO₂ atmospheres (including Venus and Mars). The SpaceX Methalox engines were specifically designed for the ability to generate fuel from the Martian atmosphere.
- Methane is relatively dense, requiring a much smaller fuel tank.
- Does not require the extreme cooling of Liquid Hydrogen which is a major engineering and reliability issue. Hydrogen, even when cooled, is difficult to store- it tends to leak.
- Generally easier to store and handle.

Hydrogen (advantages):

- Higher specific impulse.
- Easily created from water. Water is ubiquitous in the universe- in our own solar system many comets, asteroids and moons have substantial percentages of their mass as water. The only places water is relatively rare is the inner solar system where in the early solar system the new sun's radiation prevented the water from consolidating or exposed it to intense ultraviolet radiation causing it to dissociate into hydrogen and oxygen. Hydrogen in particular can be stripped off the surface or the atmosphere of a planet- as happened to Venus billions of years ago.
- For reasons of performance and access to water our original colony ships and the individual ships launched from earth all had Hydrogen powered engines. Their high performance combined with large, required quantities during the powered maneuver and asteroid redirect all dictated LH engines.

- Because of this, we have landing ships already built and available. In chapter 13 we stated that we would keep one of every ten core ships as our future landing ship- which we called hull 7. A methane ship would require new landing craft be designed and built.

For these reasons, I have selected LH for the fuel. As currently envisioned, our arriving starship will have at least 4 landing craft of a similar design to the Space X Starship. Since LH is not very dense, we would need a larger fuel tank than the Methane fueled version. That is why I conceived the original colony ships as having a diameter of 12 m and approximately 60m to 70m long. I assume no new technologies but just some incremental improvements in engine reliability (the improved SSME+ engine), insulating tiles, and aerodynamics over the current Starship.

Our landing ship would probably not be able to lift off from a large rocky planet like the earth- its engines will not be powerful enough to take off fully loaded. However, with a MR of about 7 it will be sufficient to go 9kps. The SpaceX fully fueled starship is powerful enough to lift off and go into orbit around Mars, but it is not big and powerful enough to launch from Earth without its booster. I believe a Starship landing craft with performance similar to that of the SpaceX rocket is sufficiently capable to serve in all but the most extreme circumstances.

Below I compare our proposed Colony Landing Ship with the SpaceX Starship.

	LH/LOX Landing Ship	SpaceX Starship	
Length	60m	50m	
Width	12m	9m	
Cargo Volume	1000m ³	1000m ³	
Cargo Mass	100mt	100mt	
Empty weight	200mt	100mt	Increased length and diameter to incorporate hydrogen fuel tank
m₁ Weight	300mt	200mt	With 100mt payload
Total Engine Thrust	2.3mNx 3= 6.9mN	2.3kmN x3= 6.9mN	
Isp	460sec	380sec	
dv	8.9kps	7.2kps	
m0/m1	7	7	
mo	2100mt	1,400mt	
Dimensions	60m length (tanks 50m)	50m	

TABLE 15-1 PROPOSED LANDING SHIP AND PERFORMANCE COMPARISON WITH SPACEX STARSHIP

The Landing Craft design will also have a thermal protection system (TPS) similar to that designed for the SpaceX Starship. As with the starship, a planet with a moderate atmosphere can be used to slow down a ship during reentry so that only a small amount of fuel is needed to land. Our TPS will need to permit multiple reentries with only minor repairs. We will also need robust landing legs on our ship.

If our lander ships are equipped with 3 SSME+ type engines, they will be able to provide about 6.9kN of thrust which, if combined with a reduced fuel load, will permit them to taking off from planets with a gravity of about half that of earth.

It may also be cost effective to include some straightforward landing capsules that do not have re-orbit capabilities. These could be large blunt capsules useful for landing loads on planets with an atmosphere

and very small fuel tanks with engines suitable to just do one landing. The extra storage space created by having such small tanks could be dedicated to cargo. They would land through a combination of aerodynamic drag, parachutes and perhaps a small rocket (similar to the Blue Origin retrorocket) fired to provide a cushion just before touchdown.

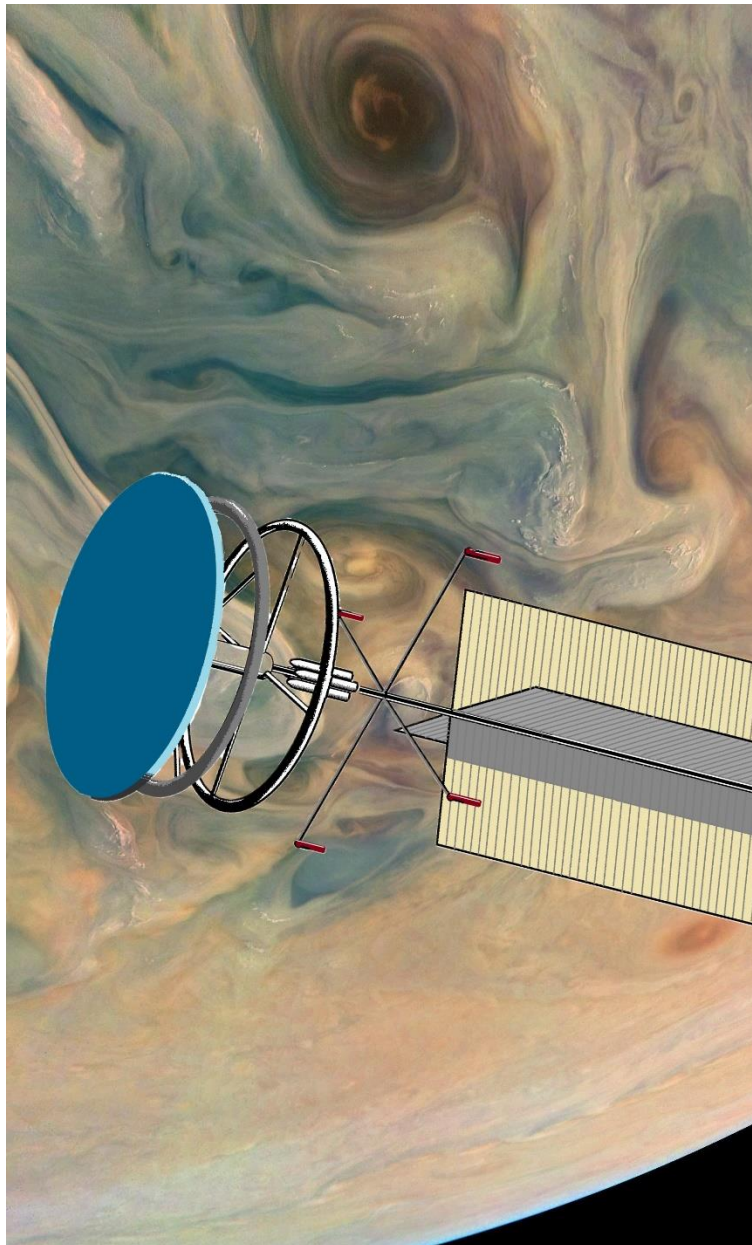


FIGURE 15-3 FINAL STARSHIP CONFIGURATION PASSING BY A GAS GIANT

Summary and Conclusions

In this chapter we reviewed Phases 6-8 of our voyage. In some ways the least thought has been given to actually colonizing the alien star system. This is partially driven by the ignorance of what star we will select and what the nature of its planets and its available resources. However, more fundamentally, humans have never attempted to build a viable ecosystem from scratch. Every place on earth already has native plants and animals, as well as the same water and air that we all breath. When we colonize an alien system, we have to build almost everything from scratch- whether we build a large space station in orbit, domed or underground cities, or, if the planet is close enough to be somewhat

earth like, terraform a world. All animals, fish and plants will have had to have been brought from earth. Except for the raw materials, everything else created will be from the hands and mind of man.

Chapter 16- Back in Our Solar System



Before we launch our starship, we need to do a lot of homework. A 10,000-year journey will require a lot of research and development, but even more importantly, a vast space industry on the scale of a large country. This is the biggest challenge. If motivated, Earth industry could probably build the MMD and starship infrastructure within 10 or 20 years... there are no major technological hurdles to doing this on earth. Building this capability in space is a whole new ballgame.

In this chapter we will talk about the Technologies, but even more importantly, the industries that will need to be developed to get ready to launch this most ambitious and challenging mission. To launch a Starship, the most important ingredient to make this doable is a Space Based Infrastructure. The following items are just some of what would be needed to build and launch our starship.

- Selecting the Star
 - o Building a telescope
- Developing our Power Supply for space use
 - o Fission
 - o Fusion
- Raw Materials
 - o Mining and transporting
 - Metals
 - Uranium
 - Volatiles
- Building and Manufacturing Technology
 - o Fabrication of useful items from raw materials like Steel, Metal, Glass, Plastic
- Building the Starship
- Building the Mega Mass Driver (and power supply)
- Making finished products
 - o Electronics
- Landing Ships

- Supplies and Equipment

Selecting the Star

If we are building a starship, we really need to pick where we are going first. In Chapter 4 we reviewed some of the target stars but no decisions as to which star should be the target could be reached as there is just not enough known about any of these stars. Deciding on what is the target star can drive some of the specifics of our mission- whether the mission is 5000 years or 15000. How far out of the ecliptic is the target star? Where will our mass driver need to be positioned and what will be its orientation?

One of the first things required is to build a telescope powerful enough to detect earthlike planets within 10 or so lightyears.

Building a Telescope

There are many large telescopes on earth, but their capabilities are limited by atmospheric distortion or filtering. Our turbulent atmosphere prevents ground-based telescopes from achieving their theoretical performance in resolution. Light pollution-the atmospheric glow from cities and urban centers- further washes out the stars.

Space based telescopes, even though they are frequently smaller than their ground-based counterparts, can achieve their theoretical limits in resolution because of this lack of atmospheric distortion. For these reasons, more and more large telescopes are being placed in space even though the costs are many times greater than for an equivalent ground-based observatory.

To determine what our target star will be, we need to identify a suitable star. In Chapter 4 we discussed these parameters. Ground based telescopes can already determine suitable stars. However, even more importantly we need to identify a star system that is able to support a vibrant and growing human population. This is much harder to determine. Even if we selected a promising star we need to determine two other items in order of importance- raw material availability (including sufficient variety of elements) and the existence or habitability of its worlds.

Analyzing the spectrum of a star gives you an idea of raw materials that should be available in that solar system. Some stars are metal poor, which indicates that they evolved in a cloud of interstellar gas that was mostly hydrogen and little dust or heavier materials. This may be an indication of a lack of rocky worlds... if these sort of star systems have planets, they may be primarily gas giants. However, this is all speculative. To be able to determine a system's suitability for a human mission, direct visual observations of planets would be needed to give enough confidence that the raw materials and planets to support a colony are present.

To directly image a planet in any sort of detail is tremendously difficult. The ability of imaging an object is affected by two things- light collection ability and resolution. Both are determined by the effective diameter of the light collector (a mirror for a reflecting telescope, the lens for a refracting telescope). As can be imagined a distant planet will be very dim, and the challenges are made all the more difficult due

to the fact that the star it orbits is on the order of a billion times brighter. Even tracking distant planets is a challenge, the telescope pointing accuracy must be extraordinary.

Light collection capabilities are related to the square of the diameter of the primary mirror or lens. A mirror twice the size will have four times the light collecting area and hence collect four times the light. Even if you could collect enough light to see the planet, the fact that the parent star is on the order of a billion times brighter means you probably could not see the planet anyway. The planet will be so close to the star that its image will be drowned out by the star's brilliance. Solutions to this have been explored by NASA and some tentative missions have been developed- though none funded. The latest version is called the New Worlds mission. It would position a large occulter called a star shade positioned around 45,000 km from a space telescope. This shade blocks out the light from the star so that a planet, if present, could be imaged. The star shade would be sunflower shaped vs a circular shape in order to get around the existence of the spot of Arago whereby, because of the wave nature of light, there appears a bright point in the center of a circular objects shadow. The sunflower shape prevents this and makes the occulter very effective for allowing our telescope to image a planet.

The next challenge is to image the planet in sufficient detail to give our colonist an idea of what to expect. With an occulter and a large telescope on the order of the James Webb Space Telescope, a lot can be determined with very low resolution. The mass of the planet and approximate diameter can be determined by its orbit and the nature of its surface and atmosphere may be deduced from its spectrum. However, to get detailed images of a planet is much more difficult. Telescope resolution is related to the Raleigh criterion previously discussed. As with Radio transmitters, the ability of a telescope to separate two points in an image is dependent on the primary mirror or lens diameter AND the wavelength of light. The resolution limit is:

From Equation 6-5 $\sin\theta = \frac{1.22\lambda}{d}$

With the wavelength of light averaging $\lambda = 550\text{nm}$ and the angle being so small we can use the approximation of

EQUATION 16-1 $\theta = \frac{138}{d}$

For a star 10 light years away, the distance would be over 250,000 times further than Jupiter's moons which implies a telescope 250,000x the diameter of the Hubble Space Telescope for the equivalent resolution shown in Figure 16-1. The Hubble telescope mirror is about 2.4m in diameter which implies the need for a telescope 600km in diameter. Clearly this is not practical but there is a technology that can get around this limit- an interferometer. In this technique, smaller telescopes can have the resolution of a larger telescope by tying them together... the distance between two telescopes can generate an image with the resolution of a single mirror with a diameter equal to the distance between these two telescopes. With optical wavelengths, this is extremely difficult- the two (or more) scopes must be tightly tied together within a fraction of a wavelength of light. Furthermore, the atmosphere of earth

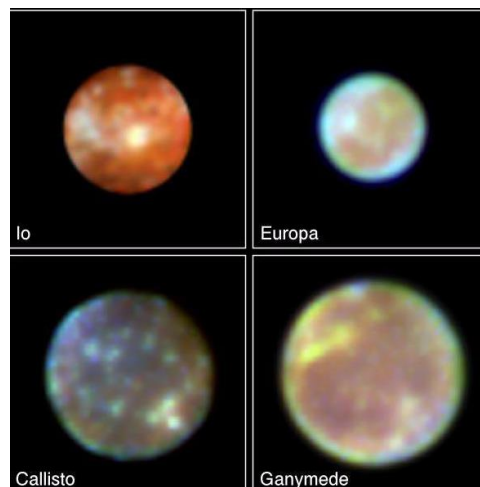


FIGURE 16-1 THE MOONS OF JUPITER FROM THE HUBBLE SPACE TELESCOPE (COURTESY NASA)

substantially reduces any telescopes theoretical performance. Nevertheless, the technology is well known and is frequently used on Radio Telescopes (where the longer frequency makes it much easier) and some optical scopes. There can be no doubt that when large interferometers are built in space they will offer unparalleled images of the universe- and should be able to form images of distant planets. Finally, besides the angular resolution, the size of the collecting mirrors would need to be large in order to collect enough light to image the planet around another star. However, with modern very sensitive imaging chips, combined with an extended exposure times of perhaps many minutes, the mirror collecting areas will not need to be 250,000x larger than Hubble. It is likely that four or five telescopes each 20m in diameter and linked together in an optical interferometer would have sufficient light gathering power to image a planet around a nearby star.



FIGURE 16-2 VERY LARGE TELESCOPE, CHILE- AN OPTICAL TELESCOPE THAT CAN OPERATE AS A LARGE INTERFEROMETER (GREGERSEN, 2019)

Developing our Power Supply

Building long lasting fission reactors in space is clearly doable- but we currently have no engineering experience. We have three challenges- designing a reactor for use in space, designing it as energy/mass efficient (watts per kg) as possible and finally, developing the space industrial capabilities to source the raw materials and actually build one. In this book we saw that 20W per kg is the minimum to accomplish our goals.

Furthermore, with a power supply that may last 25-35 years at most, fuel changeouts will require a large quantity of replacement fuel. The technology for recycling our ^{235}U along with enroute resupply will be needed.

Fission

Fission power supplies are a must for a future starship mission. Even though there have been no large space-based reactors ever constructed, the engineering of fission powerplants is well known and relatively low risk. More challenging is the actual difficulty of building and fueling of one in space. In this book we concentrated on Uranium fueled reactors since we have far more earth-based experience with them. However, one possible area for future consideration are Thorium reactors. Thorium is about 3-4x more prevalent than Uranium so may ultimately prove to be a better long-term resource.

There are several areas that have to be addressed before fission capabilities will match the requirements:

- High power density. We need fission power to generate at least 20W/kg of reactor mass. If we can produce even more efficient reactors, we could either make our starship smaller and

dedicate more mass to other items like radiation protection. Our MD driven Starship while under acceleration needed about 1.2 GW of power- its power plant weighed nearly 60,000mt. If we could increase our mass efficiency to 40W per kg this would free up 30,000mt of mass for supplies, cosmic ray protection, etc. For this reason, it is highly desirable to develop the technology to provide 40 or 50 W/kg.

- Reliability and repairability. The reactors must provide power for thousands of years. Over time all parts of the reactor will need to be changed out or repaired.
- Fuel swap out and fuel breeding/recovery. It will be very beneficial to either extend the period between fuel changeouts or to be able recycle the fuel to extract more of its residual power and reduce the amount of resupplied fuel needed.

Fusion

To me, nothing drives the point home as to how difficult fusion power is as this simple fact: in the heart of the sun, where the pressure and density are highest, the sun generates about 276.5 watts per cubic meter- or less than what is generated by a compost pile. The density at the center of the sun is about 150,000 kg/m³ or about 10 times that of gold or lead and the temperature is about 15.7 million C. The amount of power generated drops off rapidly as you get further from the center- over 99% of the sun's fusion occurs within 24% of the sun's radius.

If fusion can be developed into a practical power supply over the next fifty to a hundred years, it will be revolutionary. Furthermore, it has been speculated that not only can fusion provide the power needed for a starship, but it may also be able to provide the propulsion since a fusion reactor that "leaked" at one end would have a very hot plasma escaping at a very high specific impulse, and possibly a (relatively) high thrust. However, all is speculation and theoretical... we have not achieved anywhere near the required fusion power output, and certainly not the lightweight mass required.

Even though fusion does generate more power per kg of fuel than fission, most of the designs that have been considered are far from compact. Fusion generators may not be as scalable as fission ones, and any fusion plant developed over the next hundred years will likely be extremely massive. There are several fusion designs that are being considered and actively pursued in the quest to build a practical reactor. The so-called Deuterium-Helium 3 reaction is in many cases the best option- it creates less radioactive waste, can operate the longest before requiring a shut down due to the reactor walls becoming radioactive, and seems to offer the potential to require a smaller reactor plant per watt generated. Its biggest drawback is that He₃ is extremely rare. When considering this challenge, the easiest source for He₃ is the surface of the moon where billions of years of the solar wind have deposited small amounts in the lunar surface. How small? The estimate is that in one cubic kilometer of lunar regolith, there would be 33kg of He-3 (Sviatslavsky, 1993).

Because of these factors, I don't think fusion research will be a key requirement for interstellar starships in this century. However, I will talk about the future, longer term potential of fusion in Chapter 17.

Raw Materials and Mining

There are certain materials that are more important than others. When looking at other stars, it is very difficult to determine what resources exist in their proximity- analyzing the planets, asteroids, comets, and moons are beyond our ken. However, using our own Solar System as an example, we can make reasonable assumptions as to what may be out there. It appears reasonable that the resources needed to support extensive colonization are prevalent in most systems. Even if a solar system had only a few asteroid size planetoids a few hundred kilometers in diameter, the raw materials would be available to build very large space stations. In this book we have concentrated on keeping our colony ships small because of the difficulty of accelerating large masses across interstellar space- however a space station does not have this restriction. Its size would be limited only to the raw materials available, and the strength of the materials used. Using steel or aluminum we could build torii many kilometers in diameter, with hull diameters of hundreds, or even thousands of meters across. As we saw in Chapter 12, there are others shapes we could choose, especially if resources are available and the mass is not critical. There have been proposed O'Neill cylinders that could support millions of individuals and measure 5km in diameter by 50km long.

For our starship, most of the required materials will be delivered already separated and pure. Anything that is sent to the starship would have to be mined and separated out in our Solar System

As we saw in Chapter 4, the available resources in space are vast but we have no experience with extracting them. Identifying where the needed resources are and isolating them presents a challenge. We will need a space mining industry. The ability to mine and exploit the resources in space is required for the construction of our starship and MMD, and ultimately colonizing of our target star system.

As proposed in this book, a vast majority of our supplies for our starship and MMD will come from our two asteroids, with only some extremely low amount coming from the earth. Various metals will be needed, and these frequently do not occur as pure ore but require high temperatures and mixed with other compounds to isolate. Adding to the challenge is the fact that practices and raw materials used on earth may not be suitable for use in space.

Once the appropriate materials are isolated, they will frequently need to be combined with other materials to make something useable- with metals this is called alloying. It is outside the scope of this book to go into the hundreds of products needed but building a space industry is not trivial. Some examples of useful materials that are mixed with other elements:

Steel- is an alloy of primarily Iron, mixed with carbon. Steel is usually stronger than aluminum, but heavier. It would likely be used where strength is required but low mass is not necessary or desirable. Iron is in large supplies on the Moon and Mars, as well as M type asteroids.

There are many non-ferrous (no Iron) metals that will be useful and are available on the moon, Mars and the Asteroids. Some common ones are:

Aluminum- is frequently alloyed with copper, zinc, magnesium, manganese, and silicon to improve its strength and properties. Aluminum alloy can be used for the ship's construction. Pure aluminum is a good conductor and can be used for electricity.

Other metals, including Copper and Titanium will likely be needed, either pure or alloyed.

We also need to consider the need to manufacture large quantities of superconductors, whether to build our coils for our mass drivers, or, if available, for a fusion power plant. The most common type of low temperature superconductor material is niobium-titanium wires which have a critical temperature and need to be maintained below 10 kelvin (Charifoulline, 2006).

Plastics- on earth, plastics are frequently made from fossil fuel-based chemicals. Plastics are primarily composed of Carbon chains but can have other elements like Oxygen, Hydrogen and silicone attached. There are a bewildering number of plastics that are manufactured. Fossil Fuels are not present outside of earth so alternate means will be required to make these raw materials. However, since fossil fuels were ultimately derived from former living organisms, plastics can and have been synthesized from plants, including cotton and corn.

Benzene is one of the key elements and frequently is used as a precursor to more complicated products. On earth, benzene is gotten from coal or oil. Benzene is composed of six carbon atoms arranged in a ring with one hydrogen atom joined to each carbon atom. To make Benzene from asteroidal materials is

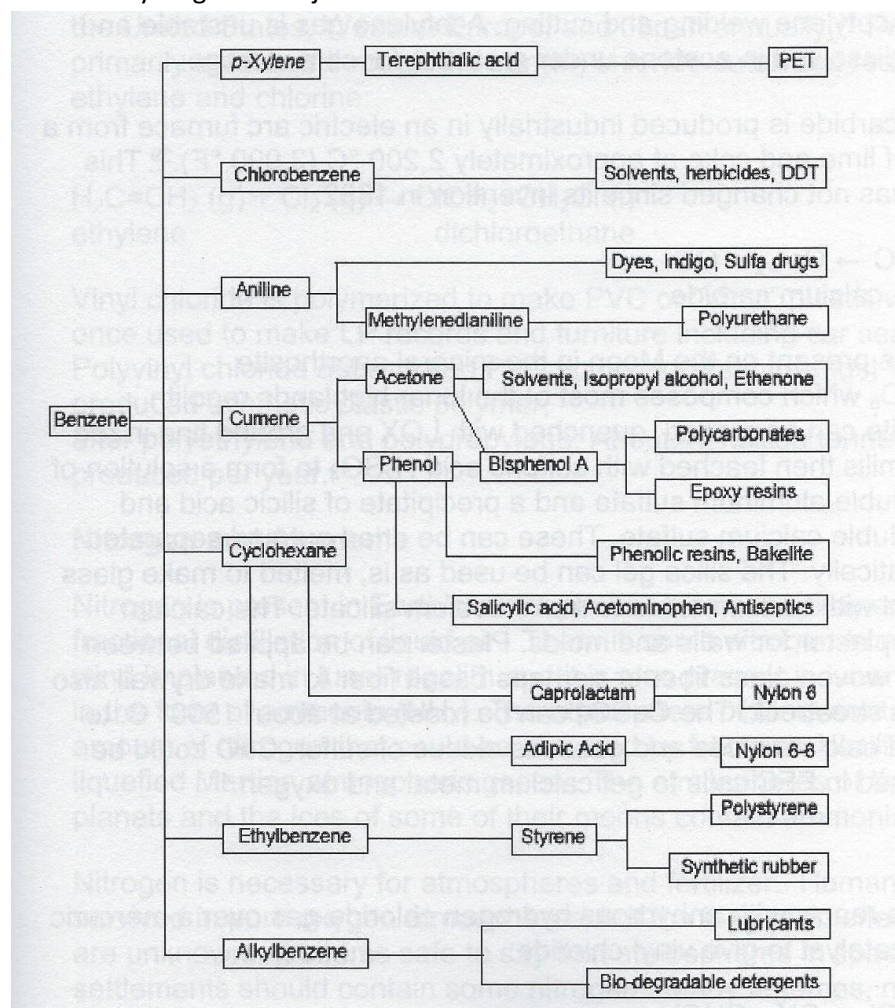


FIGURE 16-3 BENZENE AND ITS USES (DIETZLER, 2021, P. 49)

probably possible but will involve multiple processes.

The list of items that need to be able to be manufactured is substantial. Besides plastics, we would need materials like rubber and silicone for gaskets, sealants and lubricants. We will need materials to make fabrics, paper, cardboard etc. Some items like paper can be derived from Bamboo which is extremely fast growing (Dietzler, 2021, p. 61).

Finally, the requirement for large amounts of power dictates that large sources of Uranium or Thorium will be needed. Since these elements are available in space in much smaller quantities than most other items, the sourcing and extraction of these items is

likely to be a big, perhaps the biggest resource challenge. Uranium and Thorium exist in small quantities in all astronomical bodies, but determining which bodies have the largest concentration and are easiest

to extract is unknown. In this book I anticipated that the extensive mining and development of an MMD asteroid would also make available large quantities of Uranium fuel. This assumption may be overly optimistic.

Later in this chapter we will attempt to approximate how much of each raw material resource will be needed.

Glass- glass is an amorphous (non-crystalline) solid that is usually transparent. It is primarily made of Silicon Dioxide (SiO_2) mixed with other elements (frequently Soda Lime (Na_2CO_3), Boron Trioxide (B_2O_3), alumina (Al_2O_3) among other elements) to change its properties.

Ceramics- are hard, brittle, heat and corrosion resistant materials usually made of clay and fired in an oven a high temperature. Clay minerals are inorganic minerals made of hydrous aluminum phyllosilicates (water containing, along with aluminum and silicone containing minerals like vermiculite ($\text{Mg,Fe,Al})_3(\text{Al,Si})_4\text{O}_{10}(\text{OH})_4(\text{H}_2\text{O})$ as an example).

Building and Manufacturing Technology

Over the centuries of industrial development on earth, humans have learned to manufacture a bewildering number of products. Many, but not all of these capabilities will need to be created in space for both the construction of our Starship as well as the MMD. Perhaps equally challenging, this knowledge and capability must be given to our colonists so that upon arrival at their new home they will be able to construct their new civilization.

Obtaining the raw materials is only the first step. Just as important is to be able to fabricate an item into something useful. Some of the capabilities that will need to be developed in space (and carried aboard our starship) are:

- Welding- this perhaps will be relatively simple. Welding equipment is relatively small and portable. The challenges will be adapting them for zero gravity and no atmosphere
- Fabrication and foundries - the ability to pour metals into forms to shape them, or extrude them into solid blanks, tubes and piping, wires or sheets. Some common materials that will need to be formed and fabricated are:
 - Steel
 - Aluminum
 - Other Alloys
- Glass, Silicon and Ceramics
 - Making glass- equipment would have to be used to fabricate glass into a useable form (plate glass, fiber optics) etc.
 - Fabrication of silicone- for gaskets and electronics
 - Ceramics for various purposes
- Fabrication of plastics
- Concrete or its equivalent- for bracing of MMD structure, anchoring to asteroids, or cosmic ray protection
- Fabrication of electronics

- Wiring
- Soldering
- Chip and wafer lithography; manufacturing of computer chips, image chips, solid state memory etc.
- Circuit boards
- Fabrication of clothing materials and textiles

While a thorough analysis needs to be done for the thousands of items that will be required to be manufactured, many items will be needed in very small quantities relative to the volumes needed on earth. However, some things will have to be fabricated in substantial quantities including:

- MMD bucket and Starship MD buckets. In both cases millions will need to be fabricated.
- MMD and Starship MD linear accelerator sections. Each section will be virtually identical and will be bolted/fastened to the adjacent section. Each section might be only a couple of meters long to facilitate fabrication inside a pressurized environment and then can be moved easily around when completed. If each section is only a couple of meters long, some 250,000 sections will need to be built for the MMD, and about 25,000 sections for the starship MD.
- Superconducting wires. Currently the most commonly used superconductor is Niobium-titanium wire which has a critical temperature on the order of 10kelvin. Many hundreds of thousands of miles, if not millions of miles, of wire will need to be manufactured for our MMD and MD coils.
- The power plants of the MMD will be very large, requiring square kilometers of radiator cooling and large containment vessels.

While all of these items are daunting, if we are to build colonies on Mars that have hundreds of thousands of people, industrialization of a similar scale will be required. While I personally doubt that Musk will be able to achieve his vision for several more decades, this would still imply that by the 2060's or 2070's these capabilities could have been established in space. To keep it in perspective, Elon Musk has launched more satellites into orbit over the last three years than have been launched over the previous 60. Combined with launch prices that have dropped by 75% over the last ten years, and the number of launches and payload to orbit mass hitting records, leaves me somewhat optimistic that these capabilities will be achieved this century.

Building the Colony Ships

The fabrication of the Starship itself was already discussed in chapter 14.

The original four colony ships were all launched from earth with all materials sourced from earth. Only supplies that are useful for the original two-to-four-year journey to the appropriate asteroid would be brought along. We would assume that there is a high level of water recycling. Each colony ship, when assembled, will have two hulls dedicated to power- with a nominal 4MW output. The amount of power needed is likely to be only about 200kW on the outbound voyage so our reactors will be operating at a very low level. The nominal 4MW may instead be generated by a series of smaller reactors (let's say eight 500kW) then six of the eight reactors will be essentially shut down during the outbound voyage. The 4MW reactors assembly will mass about 200mt and have about 20mt of fuel. All the remaining hulls

will carry fuel for our engines or supplies for our construction operation on the asteroid (per Table 13-2). One hull from each of the four colony ships would be saved for storage and eventual exploration/landing on the target solar system.

Building the MMD

The single biggest challenge for our Starship is the MMD- both from an engineering design and manufacturing perspective. We need to build a mass driver that can accelerate a bucket and payload at 10,000g to a final velocity of 300kps. The engineering challenges are:

- Setting up a colony of engineers and construction workers. To use a rough estimate, I would say that the Asteroid Colony, like the Starship will have about 1000 personnel and will likely be colonized similar to the Starship Asteroid colony. The size of the engineering project on the MMD and the need to store a lot of power mean that this asteroid will likely begin work about 15 years before our Starship colony ships are launched.
- Develop a mass driver which can launch a 20kg packet at a velocity up to 300kps with a velocity accuracy on the order of one part per million. The MMD will need to accelerate up to 95 packets per second.
- Developing a lightweight bucket able to accelerate itself and its payload at 10,000g. Furthermore, the bucket will need to have solar panels, electronics, electric thrusters and control systems to modify the trajectory after launch and provide velocity adjustments on the order of .3mps.
- Develop a power supply that will permit us to power our MMD so that it can launch up to 95 buckets/packets per second.
- Mass producing 216 million buckets
- Building a laser or microwave relay station to power the packets for fine course adjustment.

The size of the MMD is tremendous and the materials required are uncertain. Per Chapter 11 I speculated that 10,000kg per meter mass would be reasonable and with a length of 440km the MMD alone would weigh 4.4×10^6 mt. Just as importantly, the power required would be astronomical- 86TJ per second. Assuming a MMD efficiency of 80% we will need 107TJ. Using a nuclear power source that generates $20W_e/kg$ our power supply would need to be 90,000x greater than that of our starship- it would mass 5.35×10^9 mt. This size of fission power plant would require far more ^{235}U than has been used by all the earths reactors since nuclear reactors were invented and I am skeptical that an asteroid, even a large one, would have enough Uranium even if it was totally mined out. The power plant would mass about a thousand times more than our MMD!

This is an unreasonable amount of power, but I do see several possible solutions. The problem with the MMD is that it requires a large amount of power but only over a month or so. The simplest would be to increase the packet approach speed to our starship. Raising this from 30mps, to 60mps will half the launch rate of our MMD. Total power needed would not change- it just would be stretched out to twice the duration.

If we could instead generate the required power over a couple of decades and store it, this would tremendously reduce the size of our reactors. Suppose we built a Nuclear Power plant that creates only 1% of the required peak power- or 1.087TJ (1087GJ) but had it operate for several years while we stored its power. The best method of storing this power is to use the rotational energy of a large mass (our asteroid) and then gradually decelerate it to bleed off the energy required. Kinetic Energy in a large mass like an asteroid is surprisingly high.

To keep it simple and to get an idea of the energy stored, we will assume a solid, uniform density spherical asteroid. Furthermore, I assume that the power plant constructed is only 1% of the demand for the MMD at peak output.

The formula for rotational energy of a solid sphere is:

EQUATION 16-2 $k = \frac{1}{2} I \omega^2$

Where

$\omega = \text{radians per second}$ and the rotational inertia is calculated by the equation of:

EQUATION 16-3 $I = \frac{2}{5} m r^2$

This inertia is for a body with a uniform density so is not exact.

The Asteroid that we have established our MMD on will be very large and likely the source of our stored rotational kinetic energy. As a first cut we can assume that the MMD and the packets it launches will have the following mass:

	Minimum Mass mt	Adjusted Mass mt (assume 2x minimum mass for waste and slag and rounded)	Comments
MMD	4,400,000	10,000,000	Assume about 50% recovered material is useable for the MMD
Power Supply	53,000,000 26,500,000	106,000,000 53,000,000	Assume power supply only 1/100 th size and stores power for 7 years Assume only 1/200 th required and stores power for 14 years
Acceleration Mass	450,000	1,000,000	Required for our Starship Phase 4
Deceleration Mass	3,800,000	8,000,000	Provided to our Starship during phase 5
	62,087,500	129,000,000	

TABLE 16-1 MINIMUM MASS OF MMD ASTEROID

1.29×10^8 mt is equivalent to an asteroid with an average specific gravity of 2.5 and a diameter of 4.62km.

Let us use this to calculate how much energy is in a rotating body of 129billion mt:

$$I = \frac{2}{5}mr^2 = \frac{2}{5}(1.29 \times 10^{11})2310^2 = 2.753 \times 10^{17} \text{kg/m}^2$$

Let us make the KE of our 95 MMD packets per second and our KE of our asteroid equal to calculate ω

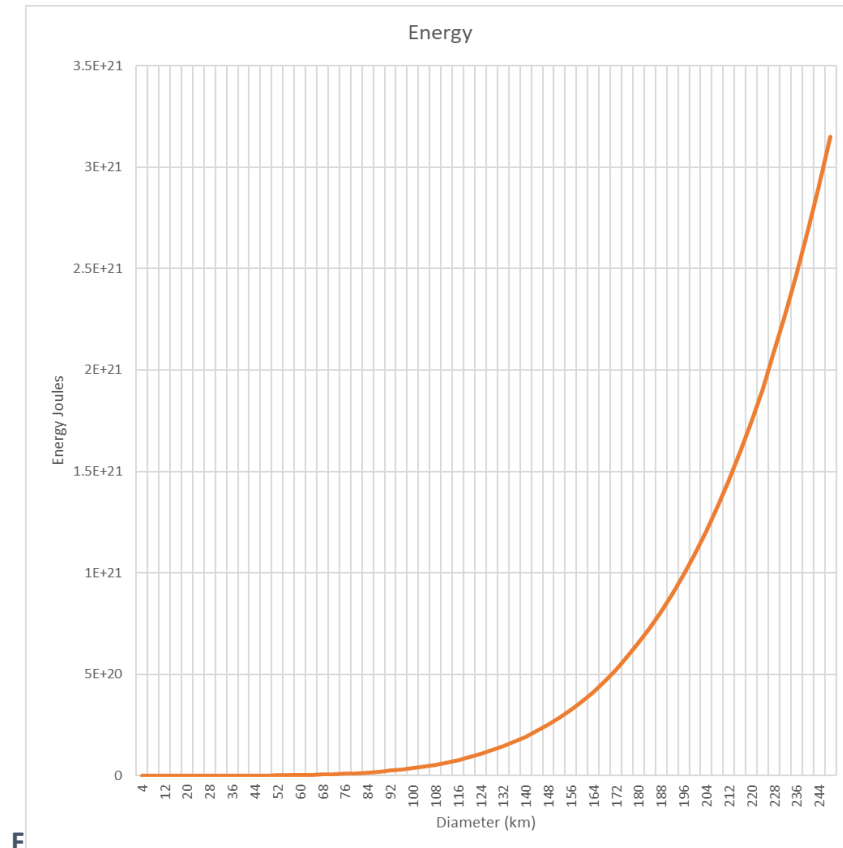
$$k_{\text{packet}} = \frac{1}{2}mv^2 = k_{\text{asteroid rotation}} = \frac{1}{2}I\omega^2$$

$$k_{\text{packet}} = \frac{1}{2}(1900) \times 300030^2 = \frac{1}{2}(2.753 \times 10^{17})\omega^2$$

Solving for ω

EQUATION 16-4 $\omega = \sqrt{\frac{mv^2}{I}}$

$$\omega = \sqrt{\frac{1.71 \times 10^{14}}{2.753 \times 10^{17}}} = .0249 \text{rad/sec}$$



F
ROTATING AT .01 RPM

This works out to about .23 rpm- too fast for a small asteroid- it would have its energy drained in a few seconds. Of course ω is a square function and builds energy up rapidly but the point is that a relatively small asteroid would not be able to provide the energy storage capacity needed.

However larger asteroids can have truly extraordinary inertia. Figure 16-4 shows the amount of energy stored in asteroids of various diameters assuming a SG of 2.7 and rotating at 1/100th rpm. If we assume we need the full amount of power- 107TJ for 26 days or 2.274million seconds or 2.43×10^{20} J sec . In Figure 16-4 we can see that this works

out to an asteroid about 151km in diameter.

We may not even have to generate the power ourselves... we could just use their current rotational energy. The largest Asteroid like Ceres has the following characteristics:

Diameter: 940km (940,000m)

Mass: 9.3835×10^{20} kg

Rotation Period: 9.07 hrs. (.00184rpm)= $\omega = .000193 \text{ rad/s}$

$$I = \frac{2}{5}mr^2 = \frac{2}{5}(9.3835 \times 10^{20})470,000^2 = 82.913 \times 10^{30} \text{ kg/m}^2$$

$$k = \frac{1}{2}I\omega^2 = \frac{1}{2}(82.913 \times 10^{30})(.000193)^2 = 1.544 \times 10^{24} \text{ joules}$$

Dividing this energy by the MMD requirement we come up with enough energy to power the MMD for 18.06×10^9 seconds or 572.6 years.

How we could extract this power is a good question. Extracting the power from an asteroid like Ceres is difficult... you have nothing to resist its rotational motion so as to extract its power. However, if we landed on a fairly large asteroid, say 100 km in diameter we can separate it into two halves, accelerate one in the opposite direction to the other using nuclear power plants (or solar power if it is an asteroid that orbits somewhat closer to the sun) over the course of several years or decades. When we need to extract the power, we would electromagnetically brake the two rotating masses against each other to liberate the energy and convert it to the power we need.

Almost all the resources will be sourced from the MMD asteroid. The exact quantities are very speculative, but it is assumed that most of the 10million mt MMD will be metal. In addition, substantial amounts of enriched Uranium will be required- assuming our rule of thumb of having 250mt of unenriched Uranium per 1000MW_e of power (Nuclear Power, n.d.), we will need 1TW of power for several years from 250,000 mt of uranium. Currently the world mines about 50,000mt per year (World Nuclear Association, 2022)... so our MMD would need the equivalent of 5 years of production. Since mass is not as important, we may even be able to use non-enriched Uranium using a CANDU type of reactor. Whether this much Uranium exists is uncertain but for now we will assume our asteroid will have enough Uranium (or thorium if it is necessary).

The total amount of packets sent to our starship came out to nearly 216million. At the peak rate of 95 per second this means our MMD will operate for only 26 days. Our reactor would need to operate for 2600 days to store enough power- which is about 7 years. If we double our reactor's run time to 14 years, we will only need half this amount of power. This is probably a more reasonable approach. For this reason, I will half the size of the power plant to 500GW and 112,500mt of uranium. If we operate for 14 years I assume for fuel changeouts- for a total of 500,000mt of unenriched or 50,000mt of enriched Uranium. Our powerplant, since it is not required to be moved, does not have to be as light weight. Assuming 10W/kg, we will mass about 53million mt.

As can be seen in Table 16-1, 90% of the required mass is needed for our MMD and power plant. And because of the huge amount of power we need for our MMD, we need a very large asteroid... perhaps

200km in diameter. Any large asteroid is likely to have more than enough material for building our MMD and its power supply, as well as our packets and most of the payloads. The MMD would probably be best built on a metal rich M-type asteroid as they should be higher in Uranium, but the size of the asteroid is so large that even an S type or C type may have enough metals to construct the MMD. The real issue would likely be sourcing the huge amounts of Uranium (or Thorium) needed and having a large enough asteroid to store all the rotational energy needed.

Starship Acceleration and Resupply

Compared to the challenges of building the MMD and its power supply, the fully assembled Starship is small potatoes. However, as they are going to be far away from the solar system, we need to be especially diligent in supplying them with the material they need.

Summary of Material Requirements

Let us consider the materials that are required. We will look at order of magnitude quantities and then identify where we can get these materials from. For materials where vast quantities are needed, we will eliminate the Earth or Venus as a source since the cost to raise these resources off the planet would be prohibitive.

We will categorize the required quantities for each. If quantities are very small (trace) I will just say <1mt. Note that for the MMD we did not specify the size of this construction operation and the crew size. For simplicity I will say it has a size similar to that of the Starship with 1000 people.

As a summary of our spacecraft weights:

Colony Ships (Earth)

Ships (hulls)	-1,250mt x 4= 5000mt	(total 40 launches from Earth)
Payload	-1,750mt x 4= 7000mt	(total 46 launches from earth at 150mt each)
Fuel (MR 6.02)	-15,068mt x4= 60,276mt	(total 402 launches from earth at 150mt each)
TOTAL Mass	-72,276mt	(approximately 482 launches)

Starship (provided by Starship asteroid)

Torus (2)	- 38,000mt	Mostly metal for shell, and silicon and clay for soil, water
Power plant	- 52,000	Mostly metal except for a Uranium fuel
Mass Driver	- 25,000 mt	Mostly metal
Shielding Mass	- 85,000 mt	Mostly water
TOTAL Mass	200,000 mt	

Note that portion of the ship hulls and payload from the colony ships will be incorporated into the Starship- but this is likely to be less than 5% of the starships mass. For the Asteroid redirect and sun powered maneuver we will expend about 4.173 million mt of LH. Depending on the water quantity in

the asteroid we will likely dispose of over 77 million mt of slag/ waste and unneeded oxygen during our initial build out and asteroid redirect.

Starship Resupply (provided by MMD Asteroid)

Acceleration mass	- 437,500 mt	(used for phase 4 acceleration)
Resupply	- 23,000 mt	Oxygen (via Water)
Resupply	-10,000 mt	Water (to replace coolant leakage)
Resupply	- 45,000 mt	Ammonia
Reaction Mass/Shielding	-465,000 mt	Water
Reaction Mass/Fuel	- 10,000	Uranium (enriched quantity. Unenriched will be 100,000mt)
Reaction Mass	-3,325,000mt	
	-2,157,750	Metal for bucket/electronics (50% of packet mass)
	-1,167,250	Miscellaneous Payload
TOTAL Mass	4,315,500 mt	(215,775,000packets)

MMD Mass (provided by MMD Asteroid)

MMD Driver	-4,400,000	Mostly metal
MMD Power	-53,000,000	Mostly metal, clay, silicate (1% of power required)
TOTAL Mass	57,400,000 mt	

Let us take a moment to identify what the volume of the resources needed are. A mass driver will have a lot of conducting wire, structure and a magnetic bucket that will primarily need metal. An M type asteroid should have plenty of all types of metals.

The Starship will likely be built on a C type asteroid... it needs proportionally much more water and ammonia than the asteroid the MMD is built on. However, the MMD asteroid will need some water and preferably ammonia for the resupply phase 5 of our starship. If the M type does not have enough water and ammonia available, these elements will need to be imported from a C type asteroid. Ammonia may be the biggest challenge- in general ammonia or frozen Nitrogen exist in the most distant parts of our solar system and the possibility exists that even a C type asteroid would have trace amounts of ammonia. If there is an insufficient amount of nitrogen, we would need to get it from the outer solar system (Titan, Pluto), a comet or Kuiper Belt object or even perhaps, the earth.

One important aspect of the summary of material list is it demonstrates that we have some flexibility on the mass ratio of our packets. We have assumed throughout this design that the packets will be 50% bucket and 50% payload. However we can see that over 1.1mt of payload is miscellaneous and unallocated. This is cushioning to our bucket/payload ratio. On average, the bucket/payload ratio could be closer to 75/25 with the bucket being 15kg if it turns out impossible to build a 10kg bucket.

In the Table 16-2 I show approximate quantity of raw materials by element required for the Starship, Starship Resupply and MMD, as well as the ease of isolating the material and handling it. These are real rough numbers, especially for the MMD and MMD power supply. However, they demonstrate the large quantities needed for certain elements.

Easy- materials are abundantly available, current technology can access and isolate. No major engineering challenges.

Medium- materials may be abundantly available but are from more distant sources. Conversely materials may be relatively rare.

Hard- materials are either very rare or very distant. May be difficult to extract without large industrial capabilities.

Item (note all referenced mass is in metric tons)	Baseline Starship	Starship Phase 4	Starship Resupply Phase 5	Needed for MMD	Possible Source	Ease of isolating or accessing	Comments
Hydrogen	0	0	0	0		Easy	From Water and Ammonia
Helium	1	0	0	1	Earth	Easy	Trace
Oxygen	140	0	0	300		Easy	From Water
Water	96,000	0	497,000	3,000,000	Water from C Asteroids, Ganymede, Callisto	Easy	Ship will leave with 85,000mt of water shielding and 1000mt as potable and 10000mt cooling. 502,000mt will be supplied enroute. 465,000 will be for cosmic ray protection, 23,000mt for oxygen replacement and 10,000mt for cooling water replacement. Assume MMD Construction Site will need more water for crops and will be less efficient with recycling. MMD will need over 1million mt for cooling
Carbon	20	0	5	400,000	From C Asteroids, Ganymede, Callisto	Easy to medium	Life for both Starship and MMD colony. Plants are primarily Carbon which they extract from the CO2 in the atmosphere. Plastics are primarily carbon. Required for Steel manufacturing (approx. 2%) on MMD.
Neon	1	0	0	1	Earth	Difficult	Rare and expensive.
Nitrogen	360	0	0	0	Titan, Venus, Earth, Pluto; C Asteroids or Kuiper Belt	Medium because of distance	Large supply to replace lost Nitrogen; shipped as Ammonia
Ammonia	0	0	45,000	800			For Nitrogen and Hydrogen
Magnesium	1	0	1	10,000	M type asteroids; most terrestrial planets and moons; Source 1 and 2	Easy	With Oxygen to produce MgO refractory

Silicon	90	0	5	50,000	S type asteroids	Easy to Medium	If required for electronics may require a lot of refining to get pure; glass; concrete
Iron	10,000	0	1	22,000,000	M type asteroids: most terrestrial planets and moons	Easy to medium	MMD is mostly Steel; MMD power plant consists of Steel and undifferentiated bulk materials; misc. Stainless Steel
Sulfur	1	0	1	10	M type asteroids: most terrestrial planets and moons	Medium	
Aluminum	78,216	0	1	5,000,000	M type asteroids: most terrestrial planets and moons		Alloys with Copper, magnesium, manganese, silicon, tin and zinc. Starship structure is mostly aluminum.
Argon	1	0	1	1	Pluto, Kuiper belt objects	Hard	
Calcium	1	0	2	2	Earth		
Sodium	1	0	1	1	Earth		
Nickel	10	0	1	1,000,000	M type asteroids: most terrestrial planets and moons have significant Nickel		For Stainless Steel, Steel, electroplating, batteries
Chromium	10	0	1	1,000,000	M type asteroids: most terrestrial planets and moons have significant Chromium		About 11% of Stainless Steel
Chlorine	1	0	1	2	Earth		Essential Nutrient; toxic; disinfectant
Phosphorus	2	0	1	4	Earth		Required for plants; fertilizer; steel making
Manganese	1	0	1	1,000,000	Earth; Moon; possibly Asteroids		Required for steel production to remove dissolved oxygen
Potassium	1	0	1	5	Earth; Moon; possibly Asteroids		Required for Life, used as fertilizer
Titanium	5	0	1	5,000,000	Earth; Moon; possibly Asteroids	Kroll and Hunter process	Fatigue limited. Twice as strong as aluminum at 60% heavier. Excellent corrosion resistance. Usually main component of Superconducting wire.
Cobalt	5	0	1	1,000	Earth; Moon; possibly Asteroids		High Performance Alloys; batteries

Zinc	5	0	1	1,000	Earth; Moon; possibly Asteroids		Alloy for Brass, batteries
Fluorine	1	0	1	1			
Copper	10	0	5	1,000,000	Earth; Moon; possibly Asteroids		Alloy of Brass; conductor; catalyst, semiconductors
Lithium	1	0	1	10	Earth; possibly asteroids		Batteries; ceramics; lubrication and greases
Rare Earths	10	0	5	100,000	Earth; Moon; possibly Asteroids		Miscellaneous for electronics and superconductors.
Other metals	5	0	2,159,000	2,000,000	Earth; Moon; possibly Asteroids		Most alloy components are only a couple percent of finished material; packet buckets will be mixture of metals and plastic. Niobium and Tin may be required for Superconducting MD and MMD wire.
Uranium	10	0	10,000	500,000	Earth; Moon; possibly Asteroids; M- type Asteroid	Difficult; Will decay over time	Most will be required for our MMD and is displayed for unenriched. MMD will generate 1/200th final power and store for 14 years. Note that Quantity for Starship is enriched which will be 100,000mt of unenriched Uranium Ore.
Soil	15,000	0	0	13,000,000			Dry Soil; Undifferentiated; contains minerals, clays, sand; Also used for MMD power supply shielding and containment
Unallocated Payload/Acceleration Mass	0	437,500	0	0			
TOTAL	200,000	437,500	4,223,036	56,062,838			

TABLE 16-2 PROCESSED RAW MATERIALS NEEDED FOR STARSHIP AND MMD (YELLOW HIGHLIGHT WILL HAVE SOME OR ALL OF THE RESOURCE IMPORTED FROM EARTH OR OTHER UNIDENTIFIED SOURCE)

There are several striking features of our starship mission resources. First is that our initial starship mass is only a fraction (.65%) of the total mass required to be refined. It is likely that 2-3 times more raw material will need to be processed and disposed of as waste or slag- the total mass to be processed is likely to be about 100 million mt.

Another highlight is the tremendous amount of Uranium needed for our MMD. As far as resupply of our starship, the primary conclusion is that only a few items need to be provided in large quantities: Water, Uranium and Ammonia. The amount of water is likely to be even higher as it will serve as a major portion of the reaction mass for propulsion and shielding. Of our 4million mt-peak mass, we will need about 4.3million mt of resupply materials to handle our acceleration and build out. Of this a minimum of 502,000mt will need to be water, 45,000mt ammonia and 100,000mt of enriched Uranium. Keeping in mind that the mass of the packets are split 50% bucket/electronics and 50% payload, so the packets supplying these three items would be at least 1.3million mt. Furthermore, the water for the cosmic ray protection was identified as a minimum of 550,000mt. This would give good protection for the occupied torus. It is likely we will want additional protection for the hub and the second tori with its power

supply. This additional water be shipped as the payload with the remaining 1,512,000mt that is unallocated.

A note about Uranium. Besides the 100,000mt of enriched Uranium needed for the starship, 112,500 mt will be needed to power our MMD for a total of 212,500mt. On the earth, our crust contains 4ppm of Uranium. Assume the asteroid has a recoverable percentage of only half this number... or 2ppm. This means that the rock processed will be 500,000x more than this or 1.0625×10^{11} mt. In reality, as on earth, the uranium will hopefully be concentrated in certain areas and this mining of low grade ore will not be necessary, but for now, I would assume that we would have to process 1.0625×10^{11} mt of ore to get the amount of uranium needed to power both our starship and our MMD. This would imply the complete mining of an asteroid 44km in diameter. This could be a major issue and may force us to consider using a thorium reactor as this material is 4x more abundant than Uranium.

Our MMD will be responsible for launching a lot of these resources. It stands to reason that, to the greatest extent possible, all these materials be sourced from where our MMD is constructed. If a large asteroid is selected for the MMD, we can likely get most of the materials needed from it. The caveats are highlighted in Yellow- these materials are not likely to be found on an asteroid and will need to be found somewhere else.

Summary and Conclusions

The biggest challenge to our interstellar mission is not building the Starship itself but building a large enough space industry that can build a structure like the MMD and its titanic power supply. If the MMD can be built and launch 95 20kg payloads per second at a velocity of 300kps with a vector that drifts only a few centimeters a year, then the Starship itself will be relatively simple!

There are several things that can be done to mitigate the size and power requirements for our starship and the associated MMD. They are:

- Reduce our proposed Starship velocity. A starship that only reaches about 200kps will need a smaller (shorter) MMD and only 4/9th the power. Furthermore, less mass will be needed for the acceleration phase, and the acceleration phase itself will be shortened. Instead of needing a Δv of 220kps we will only need 120kps, reducing our acceleration phase about 45%- to only about 40years. This will also mean that we can start increasing our cosmic ray protection about 33 years sooner.
- Reduce our $m_{1Cruise}$ spaceship size. There are three main weight drivers that we could consider reducing:
 - Power Plant size-
 - if we improved on our 20W/kg we could either make our ship smaller, increasing its acceleration, or keep our powerplant mass the same but increase our power output which would increase our acceleration by increasing our thrust. Conversely, we could use the saved mass of our power supply to increase other aspects of the ship- primarily increasing our cosmic ray protection at the beginning.

- Reduce the mass of the mass driver. As with the power supply scenario, we could use the saved mass to either make our ship lighter and accelerate quicker or use the saved mass for other parts of our ship- like cosmic ray protection. I think the opportunity for reducing the mass driver is fairly low... the mass I selected was already ambitious.
- Reduce the size of our habitation torus. Reducing the size of the torus would both reduce the mass of the torus but also, and more importantly, reduce the size and mass of our cosmic ray protection. The best option would be to further reduce our G force requirement which would reduce our radius. If .8g were acceptable, our torus radius about 22m to about 179m. This would reduce our circumference by about 10% reducing our torus weight by 10% (perhaps even more since our structure has less force and we could probably use thinner aluminum walls) but even more importantly, this also allows for more cosmic ray protection, both because of the saved torus mass, but even more so, because of the reduced radius that requires a smaller volume of cosmic ray protection.

Based on the above, I feel that a 300kps starship is a stretch goal for the 21st century and a 200kps may turn out to be much more achievable.

Chapter 17- Future Technologies and Speculation



Our challenges in building a starship are huge. In this book we attempted to reduce the risk by using known technologies. However, very large challenges remain, the biggest being the absence of a large space-based industry. If we could build and cheaply launch all the components from the earth, we could likely send out our starship within a few decades. However, with our current technology and available engines, and assuming packet resupply, our starship will mass some 4 million tons- far too much to be launched from earth. More realistically, much of the raw material along with much of the manufacturing will need to be done in space. This capability simply does not currently exist.

As a species, we have already sent out of the Solar System nearly half a dozen interstellar spacecraft. These were designed for solar system exploration and the interstellar portion was a byproduct of their mission. Some of these intrepid craft have operated for half a century. Despite this, their velocities and instrumentation are not up to the task of exploring new solar systems. Their voyage times to the nearest stars (if they had been sent in the appropriate direction) are on the order of a 100,000 years.

With this book, we have seen that with only a moderate extrapolation of current technologies, we could reduce time by a factor of 10 compared to our current probes- but even then, voyages on the order of 10,000 years are required.

Up until the designs we considered in Chapter 9, no large-scale industrial space development was needed. Beginning with Chapter 10 we require substantial space manufacturing capabilities and just as importantly, need to source a majority of our raw materials from places other than the earth. Despite my earlier insistence on using only known and demonstrated technologies, we had to stretch both our technical solutions, and perhaps even more challenging, our industrial capabilities.

In this chapter we will indulge in a little more speculation while still trying to maintain our feet firmly planted on a realistic theoretical ground- everything in this chapter is likely feasible if not currently practical.

Power and Propulsion Technologies

The following technologies are likely possible but will require considerable technological and industrial development.

Lightweight Fission Reactors

In Chapter 8 we discussed a first generation KRUSTY successor that created 10W/kg. In later chapters, as the century advanced, we upgraded to a improved but still reasonable power to mass ratio of 20W/kg. If we could further improve on this it would allow us to provide more power for our propulsion system or lower our overall starship mass. Building something that produces 30, 40 or 50W/kg would be a substantial improvement and make more mass available for payload, reaction mass or our ship structure.

Liquid and Gaseous Fission Rockets

Ramping up on our Nuclear Thermal fission engines we have liquid and Gaseous Fission engines. Similar to that of Metallic Hydrogen (covered later in this chapter), one of the biggest challenges with all such thermal rocket solutions is developing a means to prevent the rocket pressure chambers and exhaust nozzles from melting. Various methods to keep the rocket chamber walls cool have been proposed. Liquid core engines have been hypothesized to be able to have specific impulses of between 1300-1500 seconds or even 2000 seconds. Gas Core versions have been proposed with specific impulses of 3000-5000 seconds.

In a liquid core, the fissionable elements are in the liquid phase. Indeed, one type of liquid core is the Nuclear Salt-water rocket whose performance could even exceed that of proposed gaseous core.

Nuclear Salt Water Rocket

In many ways, the NSWV performance is the dream rocket for both interplanetary and interstellar travel. It has two tremendous advantages over many of the engines discussed- it has both a high specific impulse and high thrust (equivalent to chemical engines and more than the Nuclear Thermal). Furthermore, a majority of the reaction mass would be water.

The Nuclear Saltwater rocket was proposed by Robert Zubrin in 1991 (Zurbrin, 1991). Baring a fusion engine which we will consider next, it would be the highest performing engine that we will consider. Its performance is impressive- in his paper he proposed specific impulse of 7000 with the possibility of up to 10,000sec. Unfortunately, it has two primary drawbacks. First is its exhaust is highly radioactive because the nuclear material is not contained. The second issue is that it is speculative as it has never

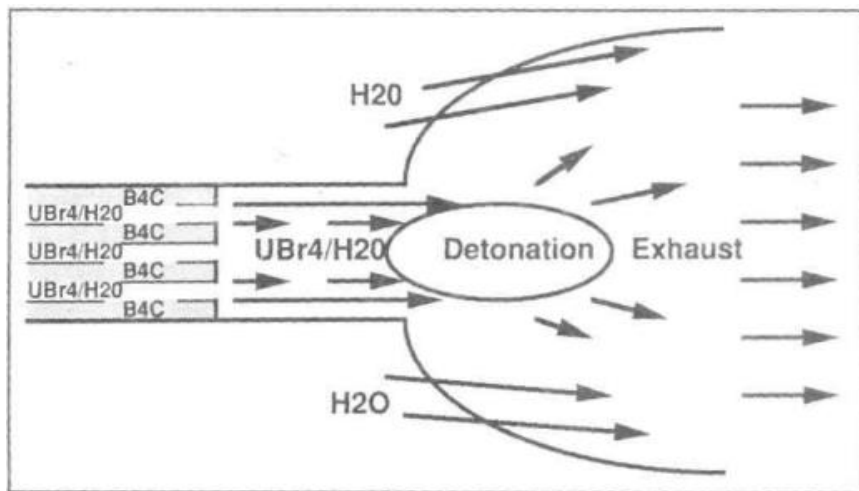


FIGURE 17-1 NUCLEAR SALTWATER ROCKET (ZURBRIN, 1991)

been built and several engineering problems would have to be addressed before we can determine if this can be a viable solution. The key aspect of these rockets is that the nuclear reaction takes place outside of the spacecraft reducing the temperature and pressures that the spacecraft rocket engine would have to handle.

If the NSW rocket could be built, the implications would be tremendous. If we take the

baseline configuration as proposed by Zubrin as a demonstration, his engine had a 6730 Isp and a thrust of 12.9 MN. In many ways the Nuclear Saltwater rocket is similar to the Orion spaceship (see later in this chapter) except it produces a continuous nuclear reaction instead of the nuclear pulsed reaction of Orion.

The NSWR opens up many options that we have not considered before. Oberth Maneuver's around Jupiter and the Sun could be maximized. Assuming an aggressive powered Sun maneuver along with a 10,000 Isp we could be approaching final velocities of 400 kps- and trip times of 7500 years. Even without Oberth Maneuvers dV could easily be 170kps with acceleration times measure in hours vs decades. Extending the performance of the rocket to a specific impulse of 10,000 we would be talking about 300kps achieved in a few hours of acceleration.

Zubrin himself, while acknowledging the large improvement in performance, points out that even under the best circumstances, an small Saltwater Rocket could achieve about 2% lightspeed, but that even a relatively small rocket would require an enormous amount of 233U, 235U or 239PU. For a 1000 ton spaceship you would need several thousand tons of fuel (Zubrin, 2023, pp. 226-227). His conclusion is that fission is just not practical for high speed missions to the stars and that fusion is required.

Fusion Rocket

In many ways, the ultimate dream for interstellar travel is the fusion rocket.

We have considered several types of fusion rockets. Indirectly solar sail can be considered a fusion rocket. It takes the radiation pressure created by fusion in the sun to provide our motive force.

More typically a fusion rocket is considered as a fusion power plant that has an intentional leak in it. Through this leak a stream of superhot plasma comes out, providing us the thrust we need. Alternately, this high energy stream could be used to heat a working fluid to generate more thrust albeit at a reduced specific impulse. If we ever build high power, highly efficient and light weight fusion reactors we should be able to also build a fusion rocket.

As we discussed earlier on fusion as a power supply, fusion has the potential to generate more power per Kg of fuel than any other power supply (other than matter-antimatter annihilation). Kg for kg it generates about 10x more power than fission. Currently the size of the confining magnets and the torus structure are prohibitively heavy. The world's biggest fusion test bed, the International Thermal Experimental Reactor (ITER), is likely to be a thousand times too heavy for our application. With ITER, the vacuum vessel (where the plasma would be generated and maintained) alone weighs some 5200 mt and if the breeder blankets and diverters are included its mass would be some 8500mt (Vacuum Vessel, Retrieved August 10, 2024). ITER is just an experiment and as such will not generate any power but its target is to generate 500MWt. This mass does not include the mass of the magnets, the power generation system, building or support structure etc. Even if designed for space, it is likely that a Fusion plant based on this design would mass over 20,000mt. To provide the power and propulsion that we have stated we will need, it is likely that our Fusion plant will need to be perhaps 10x more massive.

There are other types of fusion reactors with different principles that are much smaller than ITER. If we can develop a powerful lightweight fusion reactor, adding the ability to exhaust some of the fusion product will be tremendously advantageous as the exhaust products could be measured in the 100,000 sec range. However, the technological challenges are formidable to say the least and I do not foresee this as being a viable propulsion and power method for at least 100 years.

Solar Sailing

With the Saturn IX we considered Solar Sailing but disregarded it for large spacecraft in the near and medium future- the technology and engineering capability don't exist. In chapter X we reconsidered a less ambitious small solar sail (total mass 20kg or less) as one possible way of providing our millions of packets to our starship. However even small solar sails, perhaps propelled by a large laser or a close approach to the sun, represent a tremendous engineering and technological challenge. We don't have the materials available for building large, strong, extremely light and thin material. Their certainly exists the possibility of designing such materials and eventually mass producing them, but if and when this happens remains an open question. Nevertheless, Solar Sailing, by eliminating the engine and its power source, has tremendous future potential.

Project Orion and Daedalus

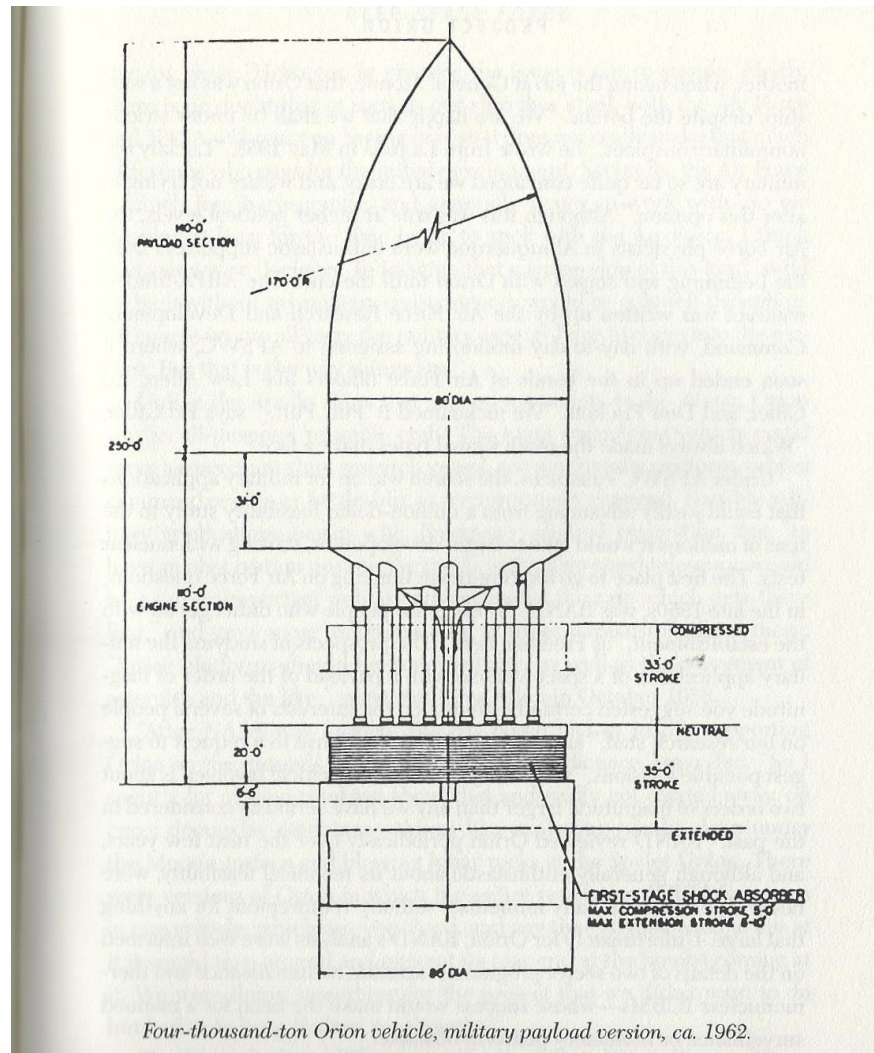
This is one interstellar technology that exists and could be built now. In the late 1950's and early 1960's the Air Force and NASA looked at the feasibility of using small nuclear bombs detonated behind a pusher plate to provide the propulsion for a rocket ship. The project was called Project Orion. Amazingly the conclusion by the government team was that this would work and provide for an extremely fast, high performance interplanetary or interstellar ship. The biggest drawback (and it was a big one) is that tens

of thousands of nuclear bombs would be needed.

Unfortunately (or perhaps not), the project never advanced much beyond the theoretical stage, and was cancelled.

Project Orion could technically be built now, though depending on the size of the ship and its target velocity, thousands or even hundreds of thousands of small nuclear bombs would be needed. A typical scenario had one bomb per second being detonated. For a starship version, a 400,000mt m_0 was considered that had a dry mass m_1 of 100,000mt. This version had 300,000 bombs of 1mt each and would reach 10,000kps after ten days of accelerating at 1g. This version was not designed to decelerate.

However, as we can see from this performance, if we reduce our velocity, perhaps to only 1000kps, we would have more than enough capability to be able to slow down at a target star as well as increase our m_1 mass considerably.



Project Daedalus was a follow up program that sought to update the concept and improve its performance. However, project Daedalus proposed the more speculative technique of fusion detonation of pellets of deuterium/helium-3. If this method of fusion can ever be successfully developed this may become our go to technique for interstellar and interplanetary travel.

Regardless, if not for the political difficulties of building a starship that has up to several hundred thousand nuclear bombs, a version of Orion powered by fission bombs would be technically the easiest and most practical method of building a starship this century.

Thinking Way Out of the Box

Throughout this book we have **FIGURE 17-2 PROJECT ORION (DYSON, 2002)** looked at what is buildable- from a fundamental physical, engineering, and economic perspective.

The following few items do not violate any rules of physics but are beyond our current technical or engineering capabilities and may be forever impractical.

Metallic Hydrogen

Metallic hydrogen can best be looked at as the ultimate non- nuclear rocket propulsion. In theory, hydrogen, when subject to extreme pressure, can transition to a metal. Furthermore, theory indicates it may be metastable, remaining in its metal form even when the pressure is released. It is anticipated that Metallic Hydrogen would be about 10 times denser than molecular hydrogen, would not need cryogenic cooling for storage, and would need no oxidizer. At a certain point metallic hydrogen would recombine into hydrogen molecules with an energy of recombination of 216 MJ/kg. It is calculated that a metallic hydrogen engine could have a Specific Impulse of 1700sec (assuming that a rocket chamber could be built where the walls did not melt). At a chamber pressure of 40bar the equilibrium temperature would be about 6700K- far more than any known material could withstand. (Silvera & Cole, 2009)

Metallic Hydrogen could be a revolutionary fuel. However, the ability to create metallic hydrogen is highly speculative- it has never been done. Experiments and theoretical work indicated several hundred GPa of pressure are required to create it- currently beyond our ability to produce.

Momentum Transfer (MT)

Spin Launch is a company currently developing a unique system to cheaply and rapidly launch payloads into space. As currently envisioned, a rapidly spinning composite arm some 45m long in a vacuum chamber will spin up to 450 rpm. At a precise moment, a 10,000kg rocket at the end of the arm will be released and

flung through a series of rapidly opening and closing doors into the atmosphere at about 2kps. After the rocket gets above the atmosphere the aerodynamic fairing will be discarded and the second stage which was protected inside the fairing on

ascent through the atmosphere, will be fired to put a small payload to orbit. By using the Spin Launch technique as essentially a first stage, some 70% of the rocket fuel and hence rocket mass is eliminated.

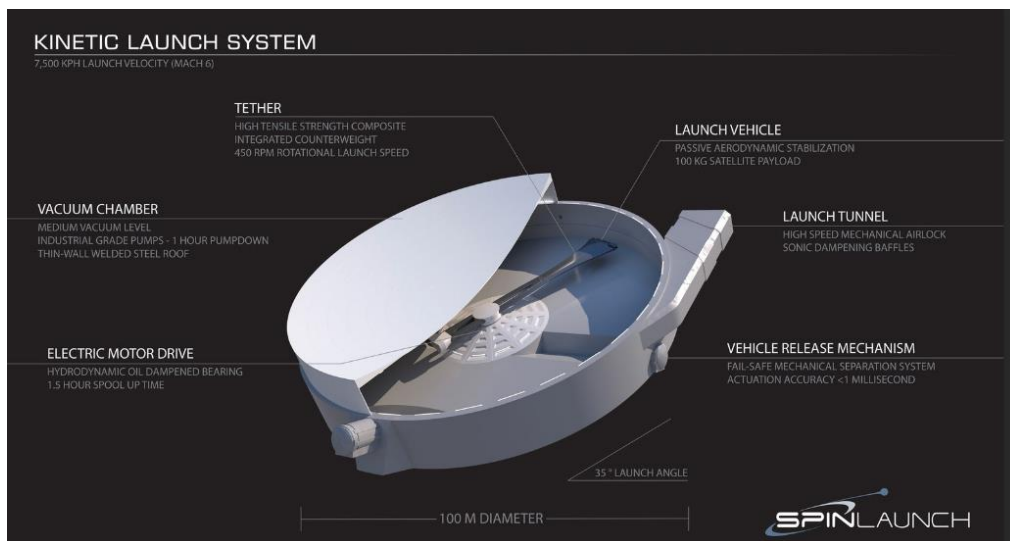


FIGURE 17-3 SPIN LAUNCH (SPIN LAUNCH, N.D.)

The concept from an engineering and physics point of view is very sound and is a type of momentum transfer device that has been considered before. The problem with this concept as applied to our starship is scaling it up... can we go much above 2kps?

Suppose we have such a far larger arm, perhaps a kilometer long, around a central hub with a payload at the end of the arm? If we spin it at 10 rpm the ends of the arm will be traveling at a considerable velocity:

EQUATION 17-1 $C = 2\pi r$

$$C = 2\pi(1,000) = 6283.1 \text{ meters}$$

Since we are doing 10 rpm the total distance traveled in one minute would be 62,831 meters. In one second, we would travel 1,047 meters so if released at this point would be traveling at 1kps.

We could also use this as a reaction mass and in keeping with the Newtons law of equal and opposite reaction, calculate the effective ISP.

$$I_{sp} = \frac{v_e}{g_o} = \frac{1047}{9.81} = 106.7 \text{ sec}$$

This would not be a very efficient rocket.

What would be the acceleration force at the end of this arm? We can calculate:

EQUATION 17-2 $a_c = \frac{v^2}{r}$

$$a_c = \frac{1047^2}{1000} = \frac{109,662,784}{10000} = 10966 \text{ mps} = 111g$$

This is far too high for a crewed payload, but well within what is possible with electronics and a properly designed structure. How fast can we spin? The Spin Launch system current concept calls for the rocket to experience 10,000g acceleration.

To figure out what our large momentum transfer arm performance can be we need to figure out how strong the spinning arm can be made. The hub is the area of most stress... it not only needs to handle our payload at the end of our arm, but all the weight of the arm from the hub outward. Because of this we would want a material that is very strong in tension but as light as possible. It turns out that except for very slow speeds steel or aluminum are not very good. Fortunately, there is a material that is being looked at for various applications whose performance is almost magical. This material is pure carbon which is made into long carbon nanotubes and is being considered for space elevators (and may be useable for solar sails). Most of the force on this arm would be tension- indeed the only reason a cable would not work would be you do need to gradually accelerate the payload by pulling it along, so a rigid arm is needed. The theoretical tensile of a carbon nanotube arm would be astronomical- in one report a variety of samples were recorded as between 11 and 63 gigapascals. 63 gigapascals is the equivalent of 9,100,000 psi or 62,742,291,368 newtons/m². (Yu, et al., 2000). With a material like this the momentum engine may be practical.

For a given material of a certain tensile strength, the formula to calculate the required cross-sectional area required is given by the formula:

EQUATION 17-3 $A_x = m_p \left(\frac{v^2}{\sigma l} \right) \exp \left(\frac{v^2 \rho}{2\sigma} \left(1 - \frac{x^2}{l^2} \right) \right)$

Where

A_x = Area Cross Section at Location x

m_p = mass of payload

v = Velocity of Payload

ρ = Density

σ = Tensile Strength

l = length of arm

Let's assume a target speed of 5kps. Currently the strength of Carbon laminate is far short of the theoretical strength but a still impressive 4.18 GPa. We will assume the following values:

m_p = mass of payload = 20kg

v = Velocity of Payload = 5,000mps

ρ = Density = 1800kg/m³

σ = Tensile Strength = 4.18GPa = 4.18x10⁹Pa

l = length of arm = 1000meters

$$A_x = 20 \left(\frac{5,000^2}{4.18 \times 10^9 (1000)} \right) \exp \left(\frac{5,000^2 (1800)}{2 (4.18 \times 10^9)} \left(1 - \frac{0^2}{1000^2} \right) \right)$$

$$A_x = .026 \exp(5.38(1))$$

$$A_x = .026m^2$$

This seems very encouraging. If we keep our arm diameter at 1000m and raise our velocity to 8kps our arm cross section area at the hub becomes a ginormous 296m². Indeed, the hub thickness area grows extremely rapidly with increasing velocity. Increasing our arm radius to 100km would bring this back down to only 2.955m², but raising our speed to 10kps raises our hub cross sectional area to a truly megginormous 10,732m². To get our arm thickness back down to a little over 2m² would require an arm 500,000km long.

For lower velocities the momentum transfer method provides a low tech alternative and efficient way of transferring large amounts of mass- be it supplies or even spacecraft. For a spin arm of 10km radius it looks to be practical for speeds up to 7kps and payloads of perhaps 100kg. For one with a 100km arm, speeds of 8kps may be practical. Furthermore, if the strength of the carbon laminate is improved so that it is closer to theoretical values, far higher speeds can be reached. If we could have a material that was good up to 50GPa, and built an arm 100km long, we may be able to get up to over 28kps. This is probably the upper limit.

The momentum transfer arm with a modest 6kps performance would be an area of low risk from an engineering design and industrial perspective than a mass driver. Nevertheless, the spin arm itself would be massive. Furthermore, it is desirable to have two spin arms, spinning in opposite directions around a common hub to conserve angular momentum. Both would release their payloads simultaneously.

Even though the Momentum Transfer does not look practical for our Starship, I could see this making a meaningful contribution to interplanetary voyages. For many interplanetary voyages 6 or 8kps may be more than enough performance for sending cargo anywhere in the solar system.

Photon Rocket

A photon rocket would be an ideal rocket in a sense that no fuel or reaction mass would need to be carried. In many ways we have already discussed a photon rocket- a solar sail- except that with a sail we are using the sun's photons for momentum instead of creating our own. A photon rocket has to generate its own photons, and as opposed to a reflective solar sail it does not get the bounce back effect that a solar sail has, where each photon gets reflected, hence doubling the force.

The problem with the solar sail as with the photon rocket is that the amount of thrust from the exchange of a photon's momentum is truly small and to get any reasonable acceleration you have to have a huge number of photons. With the photon rocket, the light output would need to be incredible (as would be the energy required to generate it) that it would not seem to be a feasibly short or mid-term solution to building our starship.

The advantages and disadvantages of a photon rocket over a solar sail are intertwined.

Advantages-

- No need for a large sail and the complexity and design challenges it brings.
- Flexibility on direction. You do not need to be near a star to get thrust or positioned within the center of a coherent laser beam. You can decelerate just as easily as accelerate at your target star.
- Far less power than a beamed solar sail. With the beamed Solar Sail, we used as our rule of thumb that we would only be intercepting about 10% of the beam so the laser on a beamed solar sail system would have to be 10x larger than the actual power being captured. Effectively with our photon rocket, every photon created could be used for thrust.
- Overall less logistics complexity. With the beamed solar sail, not only did you have to have a massive power supply built somewhere in the Solar System, but you also needed powerful lasers along with a huge lens to focus the beam.
- A "photon rocket" sounds cooler than a "solar sail"

Disadvantages

- The power supply now has to come with you. Even though the power required would be perhaps 10x smaller than that of a solar system based beamed system, it will still have to be truly massive. At least with the solar system beamed system, you could use the tremendous power available from the sun. With the photon rocket, you will have to provide all this power from your fission or fusion generators.

- Photon for photon, we have about half the thrust since we do not get the rebound effect of a reflective sail.

On balance, compared to beamed Solar Power, the advantages may outweigh the disadvantages. A photon rocket would be most practical if we could build a very lightweight but high-power reactor.

And what a truly astronomical amount of power you would need! The amount of power to generate your photon force is described by the equation:

EQUATION 17-4 $F = 1000\left(\frac{w}{c}\right)$

Where $w = \text{watts}$ and c is our speed of light in mps.

To get 1 nt of force you require 300,000 watts. Remember when we looked at electric thrusters like VASIMR? The engine we considered used 200kw for 5 nt of force. With a photon rocket, to get 5 nt of force, we would need 1.5 MW or 7.5x more power. In reality, the situation is worse since this 1.5MW is photon energy. During each step of converting our nuclear reactor thermal energy to electrical and electrical to photonic there will be an energy loss. Fortunately, it appears electrical to photon conversion efficiency is rather high- modern lasers frequently operate at over 50% of electrical to photon conversion which is good news as anything not being used to generate a propulsive photon is going to exist as waste heat (which interestingly will also create a force but likely not in the correct direction) and keeping a continuously firing laser cool will be a challenge. Regardless we will optimistically need about 3MW_e for 5nt of force.

Using the above numbers to get a 100nt thrust with 50% laser conversion efficiency we would need 60MW_e. This power supply would weigh about 3000 metric tons if we use our improved reactors that generated 20W/kg. If we attempted to achieve the 19,000nt thrust as with our proposed starship we would need 10.14GW- or over 10x more than our mass driver required and our power plant alone would mass 500,000mt.

The 800-pound gorillas in the room is the fact that building such a large fission reactor would be a tremendous challenge, and would require vast amounts of uranium. Furthermore, building a laser able to handle 10.14GW is beyond our manufacturing capabilities. Nevertheless, if we could build very high power but light nuclear reactors (either fusion or fission) of 200w/kg or greater, a photon rocket could become an attractive option.

Antimatter Rocket

In many ways, the most direct way of making a Photon Rocket is with antimatter. When Antimatter and regular matter come in contact they immediately annihilate and depending on what materials were used will release neutrino's, gamma rays and some less massive particle and antiparticle pairs like pions. Antimatter is influenced by gravitational fields just like regular matter. Antimatter molecules have the same mass but the opposite charge but in all respects are identical to regular matter. A pure antimatter world would have the same chemistry and physics as ours. However, antimatter and matter will annihilate on contact with each other releasing the amount of energy expressed in Einstein's famous equation $E=mc^2$.

When antimatter and regular matter annihilate, they produce about 100x more energy per unit of weight than the best fusion reactions, and about 1000x more energy than fission reactions. A matter/antimatter reaction would release about 9×10^{16} J/kg. A 1 kg reaction of antimatter with 1kg of regular matter would release the energy equivalent of 43 megatons of TNT- making it close to the largest nuclear explosions ever tested- the USSR Tsar bomb. A few kg of antimatter would be more than enough to launch a large high-speed starship. If only it were so easy...

One key point to understand is that while antimatter has the potential to provide astounding amounts of power for a very small mass all the antimatter must be created artificially, which is not an easy task. Antimatter does not appear to exist in the universe in bulk quantities. All antimatter has to be created in various types of particle accelerators. These accelerators require vast amounts of power to create infinitesimally small amounts of antimatter. So, while antimatter can release tremendous amounts of power quickly, the reality is that many times more power is required to create that antimatter to begin with. Even if antimatter creation were 100% efficient you would still need to get that power from somewhere... you cannot create more power than you put into the system. All you would be doing is converting the energy from a large power plant from one form of energy (coal, oil, Nuclear, Wind, Solar) into another- antimatter. It might still make sense to consider antimatter because of how compact the power source is, but somewhere you will have to have a huge power source to make the antimatter possible in the first place- likely operating for many decades or centuries to make enough antimatter for a starship.

In addition to the formidable challenge of creating antimatter, handling antimatter is a major concern. Since antimatter will annihilate on contact with normal matter, the only way to store it is to magnetically suspend it in a vacuum. We have the added problem that if your containment were to fail, the antimatter could drift into the containment vessel walls and detonate, destroying the ship.

One positive aspect of considering antimatter for a rocket is that antimatter and its properties are well known. A fair amount of the energy generated in a matter-antimatter reaction is unusable- including the neutrino's and perhaps the gamma rays. Nevertheless, there is so much energy released and many possible propulsion schemes that can be used to provide fantastic performance. Sometimes it can be a direct conversion on contact with regular matter, but in other scenarios the intense energy could be used to catalyze fusion reactions that would provide a majority of the power. This would substantially cut down on the antimatter needed.

Artificial Womb

The vast majority of this book is dedicated to increasing our propulsion performance and attaining higher speeds, developing powerful long lasting power sources, and developing spacecraft and systems that can last for thousands of years. Because of technological and engineering limitations, while we can approach much higher speeds than currently attained, none of the solutions considered got our Starships much above .1 of 1% of light speed. Because of this we leaned towards a generational ship with voyages of thousands of years. This required large colony vessels which, because of their size, drove additional challenges of power and the need to move tremendous masses.

Artificial womb technology is a developing technology that may have considerable impact to deep space missions. In it, either frozen embryos or frozen sperm and eggs that are fertilized (either artificially or

otherwise) would gestate and be born in artificial wombs instead of needing females to reproduce. Depending on how this technology is implemented this technique could:

- Substantially reduce the crew size. We may be able to quickly ramp up the population as needed without having a substantial number of females. For a majority of the mission the crew may be only a few dozen individuals needed to run the ship and perform critical maintenance. A few children would be raised at any time to replace the aging crew members.
 - o The smaller size could allow for a much smaller ship, with the attendant reduction of both ship mass and the mass required for radiation protection.
- Reproduction is very sensitive to radiation levels... leading to sterility in men and woman. Furthermore, fetus's and children are less tolerant of radiation. If the reproduction is performed in a highly radiation sheltered portion of our ship, this will lessen the need for extensive radiation protection for the rest of the ship- again leading towards less mass.
- Artificial wombs fertilized via either frozen embryo's, sperm or egg cells, will eliminate the need for mixed crews. Crew make up would become independent of the reproductive requirements and can be determined based on other criteria.

Despite having some potential advantages for a starship, the Artificial Womb concept has several issues. Currently this technology is not very far advanced, partly because of ethical and religious concerns. Currently 17 countries either have a law or guidelines that does not allow experimentation on human embryo's past 14 days (Morber, 2018).

Suspended Animation

What about suspended animation? Unfortunately, this is another questionable solution. Suspended animation is the artificial inducement of a sleep like state that drastically slows down the metabolism. It has tremendous potential on voyages and to name a few:

- Reduced consumption of resources. Most of the crew (perhaps all) will be in suspension at any one time, reducing requirements for food, space, air etc. We could conceive of a small group, perhaps 1-2% that are conscious at any one time. The other 98% of the crew would be in suspended animation.
- Smaller starship. Besides less resources being consumed; you will need less space and facilities for the crew. If 98% of a thousand crewed Starship are in suspended animation, this means only 20 crew members would be awake at any one time. No need for large "crop" growing areas, buildings, conference rooms, entertainment complexes etc.
- Reduced boredom. Only a few people would likely be awake at any one time to monitor systems and respond to emergencies. This task would likely be rotated- you may be roused for a one year "tour of duty" every fifty years. One year in even a small vessel is very achievable.
- Life extension. One of the implications (not completely accurate) is that when in suspended animation, the aging process would also get suspended or at least, slowed down. If a person is only awake 2% of the time, this implies that over a 1000-year mission he would only feel as if it was 20 years. It is possible that a person leaving the solar system could actually witness his arrival at a target star! A strong advantage and motivation indeed.

The problem is that humans were not designed to hibernate, and we are no closer to inducing hibernation in an individual now than we were 100 years ago. This does not mean it is impossible

(though it may be), but it does mean that we don't know how to do it. Hibernation, in many ways, is a game changer at least as significant as solar sails and high-power fission or even fusion reactors in space.

The Ideal Interstellar Spacecraft

The dream interstellar spacecraft, while still obeying the known laws of physics, would need a very high specific impulse of at least 100,000 sec. A specific impulse this high would allow velocities of 300kps with no inflight refueling required. A mass ratio of 1.35 would be needed for acceleration to 300kps. To accelerate and decelerate a mass ratio of only 1.82 is required. This would permit either a more massive starship with less fuel or, alternatively, give us the option to increase our velocity. If we wanted to double our velocity, our total mass ratio for acceleration and deceleration would raise to only 3.31- still very favorable.

In addition to this high specific impulse, we need a high thrust. If the rocket puts out only a few newtons, we may take thousands of years to accelerate. Lets assume the following specifications for our dream rocket:

Specific Impulse: 100,000 (exhaust velocity 1,000kps)

Mass flow rate: 1kg per second

Target velocity: 600kps

M_{1acc} : 2,650,000mt

M_{1dec} : 1,456,000mt

M_0 : 800,000 mt

Our acceleration phase will last 37.9 years and deceleration 20.8 years. Now we have a starship! The technological problem remains primarily energy... to accelerate 1kg of reaction mass per second to 1000kps will take 500GW of continuous power. This is a huge amount and assumes no waste heat. As we have seen, a nuclear plant typically converts only about 1/3rd of its energy to electrical power so we would need to generate about 1.5 TW of thermal power which will need to be radiated to keep cool- not an easy thing to do in the vacuum of space.

Issues like this are one of the reasons that the Orion and Daedalus projects are so appealing. Their nuclear reactions are energetic and powerful but occur outside of the spacecraft where a large percentage of their waste heat emits directly into space. Furthermore, there is no conversion of the nuclear energy to electrical- the energy of the detonation directly impinges on a pusher plate eliminating the conversion losses.

Technology Review, Potential and Maturity

The following is a list of the technologies we have looked at, the status of their design, their future potential, and whether they provide possible tools for building a starship.

NASA (and other government agencies) have a system that defines the technology readiness level of a new technology. The lowest level is Basic Research (Technology Readiness Level (TRL) 1 and goes to TRL 9 which is "in operation".

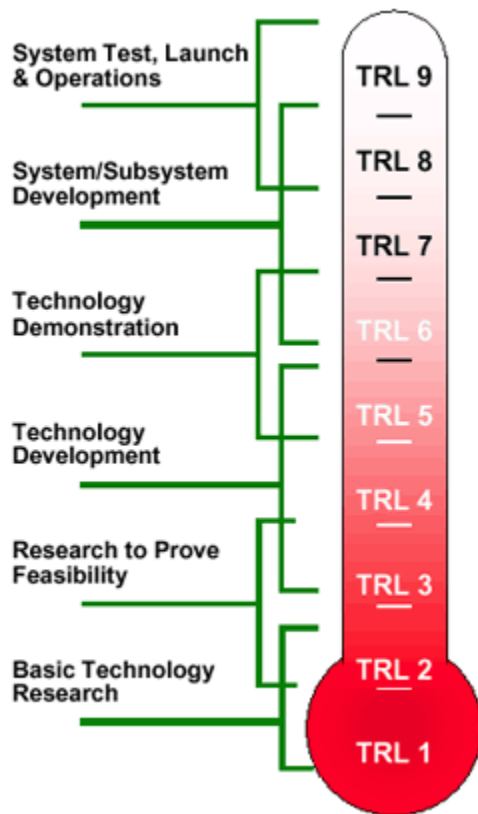


FIGURE 17-4 NASA TECHNOLOGY READINESS LEVELS (COURTESY NASA)

I have developed a streamlined and simplified version and put the technology in various buckets of Status as follows:

In Use- no changes required except perhaps scale. Little additional engineering required. Equivalent to TRL 9.

Tested/Prototyped- technology has been extensively tested but is not mission ready. May have been developed for earth use and will require additional engineering to make suitable for flight. Minimal additional engineering required. With modest investment, should be flight ready with 10 years. Equivalent to TRL 7-8.

In development- some additional engineering required. Principles have been demonstrated in the laboratory but not all engineering issues have been identified or resolved. A moderate amount of engineering still required. May need the development of some space-based industry. With modest investment, should be flight ready withing 20 years. TRL 5-6.

Potential- principle of operation well understood but major design gaps exist. All issues are believed resolvable. May involve the development of a large space-based industry. May be flight ready, with modest to large investment within 30 years. TRL 3-4.

Speculative- principles of operation understood but major, perhaps unmanageable engineering issues exists. May never be practical. May need the development of a very large space-based industry. Likely require 50+ years of sustained effort to achieve. TRL 2.

Highly Speculative- principles of operation generally understood but may never be practical and substantial challenges exist that may never be resolved. May need the development of a very large space-based industry. Likely 100+ more years of scientific and engineering progress will be required. TRL 1 or lower.

One item to keep in mind is that the NASA TRL thermometer addresses pure technological readiness. In my five categories I have awkwardly combined the technological readiness level with industrial readiness.

Power	Status	Potential Improvements	Criticality toward interstellar travel
RTGs	In Use	Longer Lasting and slight efficiency improvements.	Not suitable. Insufficient power and low conversion efficiencies make this not suitable for interstellar missions.

Stirling Generators	Tested/Prototyped- Tested but not flown	Efficiency improvements; reliability improvements	Not suitable. Insufficient power supply for interstellar missions. Much higher efficiencies than RTGs but still only able to provide low levels of power.
Fission Reactors	In development- Earth based designs are a mature technology	Need to be developed for space. Challenges are building for the space environment, extensive cooling needs. Lighter designs- Increase watts per Kg	Suitable. Need to have methods of refueling and repairing in space. Best 21 st century option. Improvements can be made by increasing the watts per kg efficiency.
Fusion Reactors	Potential	Unknown. Need to improve performance and generate equivalent or more power per kg than fission reactors.	Suitable but unproven. Will need many more decades to develop.
Propulsion			
Chemical	In Use		Not Suitable except for powered maneuver.
Electric Thrusters/Ion Thrusters	In Use	Greater Thrust, mass flow and power handling. Alternative materials for ionization including hydrogen	Likely not Suitable for large vessels- thrust fuel mass flow is too low. May be suitable for automated probes.
Mass Driver	In development- Well known technologically but never built on large scale	Electronics and superconducting materials.	Suitable only for large vessels. Greater thrust and efficiency than electric propulsion engines, but much more massive
Solar Sail	In development- Well known technologically but never built on large scale. Very light high performance Sails are still in Potential development stage	Reduce mass via extremely light, large scale and strong materials	High area of potential but will need to substantially improve our sail material to be much lighter and more durable- on the order of 100x improvement required. Will need several more decades to develop.
Fission Thermal Rocket	In development- Well known technologically but never used in space	Greater Thrust, reliability mass flow and power handling. Alternative materials for handling high temperatures	Suitable and built but never deployed. Has great theoretical potential.
Fission Saltwater and Gaseous Fusion	Speculative	Greater I_{sp} and Thrust	Suitable but unproven, has great theoretical potential.
Fusion Propulsion	Speculative	Need to develop portable fusion power supplies first	Suitable but unproven.
Photon Rocket	Speculative; physics well known	Requires very high power but lightweight reactor. Requires extremely large laser or photon generating machinery	May never be practical. Physics is well known and doable but require advanced technology including an extremely high power but lightweight power supply.
Momentum Transfer	In development	Earth launch systems are in development. However for starships performance needs to be at least 10x greater.	Not practical for over 25-30kps with even the most optimistic material strengths. Physics is well known, and modest performance is doable but advanced carbon materials needed.
Antimatter Rocket	Highly Speculative	Develop more efficient ways of generating antimatter.	Suitable but of unproven and questionable advantages. May never be practical. Takes

		Develop better containment methods	much more energy to create antimatter than you can recover.
Other Key Technologies			
Artificial Womb	Speculative		Suitable. Will likely be doable but will require extensive further development.
Induced hibernation	Highly Speculative		Suitable but unproven. May be impossible without major genetic modifications to humans.
Is Situ Resource exploitation	Potential		Suitable. Substantial engineering development required but principles are well known and have been applied for centuries on earth.

TABLE 17-1 ENABELING TECHNOLOGIES AND THEIR STATUS

Related to the need for technological innovation, one of the biggest barriers to building a starship is related to the last item and the need to build a substantial industrial base. Currently, the only resource used in space is solar power. To be able to build a viable starship would require the development of whole new space-based industries including mining, material processing and manufacturing.

Summary and Conclusions

In this Chapter we looked at alternative technologies that, in many cases, would tremendously simplify our starship mission. Many of these technologies are doable... the issue is whether or not they are economically justifiable.

Some basic areas need to be addressed in order to make a Starship of the sort envisioned in this book a reality. The most important ones:

- Development of a large space infrastructure
 - o Large, manned self-supporting colonies
 - o Extensive resource mining including for water, nitrogen, metals and Uranium.
 - o Development of large power supplies, both Solar and Nuclear
- Specific Technologies
 - o Development of large mass drivers
 - Able to provide high accelerations.
 - Electronics and instrumentation for our bucket
 - Ability to mass produce buckets.
 - In the case of our starship mass driver, we need a lightweight design.
 - o Development of large lightweight fission plants
 - o Development of large power storage technologies for an MMD. This is one area that was passed over rather lightly in this book. While the technology is relatively straightforward, it requires a lot of industrial advancement to be practical.

Chapter 18- Conclusions



Summary of Methods

We are now coming to the end of our journey. Throughout the book we looked at various technologies and methods of building a starship this century. Some conclusions we have drawn:

- Specific Impulse is critical. Chemical and Nuclear Thermal Rockets on their own are not viable for starship propulsion because they cannot get to a star in a reasonable timeframe with a reasonable Mass Ratio. The bare minimum we need to be considering are Specific Impulses of 10,000sec.
- Because of the laws of mechanics, high specific impulse helps with your final speed and minimizes your mass ratio BUT this also means your rocket is very energy inefficient. Doubling your specific impulse squares the power needed. The end result is that usually if we have a high specific impulse, our thrust is either very low, or you need tremendous amounts of power. The end result is you need a huge power supply to run your mass driver or electric thruster engines. Only advanced nuclear fission, fusion or beamed propulsion can provide the necessary power.
- Because of this, power requirements for the starship, in particular when accelerating or decelerating, are very high. Large but lightweight fission reactors are needed. $20W_e/kg$ is the minimum- but $30W_e/kg$ or more is better and very desirable.
- Requirements for large multi-generational crews, robust cosmic ray protection, large amounts of power, and substantial repair capabilities will drive the need for a large starship.

- The very high mass of the rocket, driven by the need for large nuclear power plants and long, 10,000-year missions with a crew, combined with relatively low thrust means that we need to provide thrust for many decades or even centuries.
- Packet intercept for both reaction mass as well as to assemble our spacecraft tremendously reduces the initial size of our starship (by at least a factor of 20) and until very powerful but lightweight power supplies are created combined with propulsion systems with specific impulses of 100,000 seconds or more, are likely the only mechanism to make interstellar travel feasible.
- Despite the relatively large and massive power plants that we require, the single biggest driver of our manned starship mass is the need for radiation protection. Radiation protection easily weighs several times more than the combined weight of our habitable torii, power supply and mass driver.
- Due to the long flight times, unmanned machines are not considered for several reasons. These are:
 - o Unmanned missions that last for thousands of years will not be motivational enough to be funded, built and supported for centuries. The scientific payback would likely be minimal... over those 10,000 years large solar system telescopes are likely to have been built and thoroughly explored alien solar system well before any starship arrived.
 - o Limited scientific utility from an unmanned probe. While each planet is unique, they are still fundamentally made up of the same materials as the planets in our solar system. We will not discover any new physics, forces, chemistry, or geology from a mission that may last 10,000 years. With the exception of finding aliens or alien technology everything we need to know is likely to be able to be observed or discovered either within or observed from our solar system.
 - o Reliability. Since flight times will be on the order of 10,000 years there are no mechanical or electronic devices that could last that long. You must have the ability to repair the equipment, including manufacturing of new parts.
- A majority of the raw materials for construction of our starship along with the MMD will have to come from space. To launch the mass of equipment and materials required from earth would be astronomical, requiring tens of thousands of launches. It will be far easier to send a much smaller material processing and construction facility to an asteroid(s) and build your starship by using the mined materials.

A summary of all the starship designs we have considered is in Appendix F.

Why should we go?

With all the engineering and social challenges associated with a crewed mission, the question becomes should we even go to the stars? This is a reasonable question and needs to be addressed.

It is likely that over the next thirty or forty years, telescopes in space, and perhaps even on the ground will be able to directly image earth size planets orbiting around nearby stars. So why travel and colonize? The raw materials in our own solar system are adequate for our needs for hundreds of millions

if not billions of years and by traveling to the stars we will (likely) not be making any fundamental discoveries- so why go?

Diversity minimizes the chance for extinction

Currently our species is limited to a single planet. As long as we are tied to this one planet, we remain vulnerable to species extinction events. Even if an event does not cause complete extinction, the impacts to an exclusively earth-based civilization can be severe and may take centuries to recover from. We have different levels by which our civilization can expand- first by populating the earth orbit and Lagrangian points with large space stations, colonizing the moon and Mars and then the moons of the outer planets, the asteroids, Kuiper belt and Oort cloud. The first step in this colonization is to make these colonies self-sufficient. Each independent and more distant but self-sufficient colony is further insurance against extinction.

The ultimate survival insurance would be to start colonizing the stars. Even a solar system catastrophe would not mean elimination of the species. Such expansion would provide both greater knowledge, engineering advances, and species security, as well as providing opportunities for diverse and creative experiments in civilization.

Species extinction, while a remote possibility in any one particular year, is a guarantee over long enough times. Being on one planet increases the chance of extinction sooner rather than later. With some planning and efforts, the chance for extinction in the short and medium terms can be substantially reduced by space colonization. Some examples of possible extinction events are:

Extinction Cause	Description	Short Term (next thousand years)	Long Term (1000 plus years)	Mitigation
Impact Event	Impact event from a large meteorite, comet, or interstellar body transiting our solar system have occurred in the past (i.e., the dinosaur extinction) and remain a possibility. Statistically over the next billion years this will likely happen.	Low probability	High probability	Human expansion to the Moon and Mars and other planets and large space populations will eliminate this as an extinction threat. Active planetary defenses will also mitigate.
Sun	The sun will run out of nuclear fuel in the next four billion or so years and expand to a red giant. Before this, sometime within a few hundred million to a billion years the gradual warming of the sun (about 10% warmer per billion years) will cause the earth to resemble Venus and to become uninhabitable. After this the sun will continue to grow hotter until it runs out of hydrogen and then expands into a red giant powered by helium. At this point things get worse- the earth may either be engulfed by the expanding sun or be	Near zero	Guaranteed. The sun is gradually warming as it runs out of fuel. The Earth will only be habitable for about 1 billion more years.	Human expansion to distant moons and planets will delay this threat but eventually the sun will still become extinct. If we are within our Solar System, the only solution would be advanced fusion power which could power our orbiting space colonies and world ships for many more billions of years. Migration to the Stars would eliminate this threat.

	heated to several thousand degrees and become molten. After this period the sun will shrink to a white dwarf. Assuming the earth did not get vaporized during the sun's expansion, it will be left a cold, dead cinder.			
Carbon Sequestration	This is much more immediate. All plant life requires Carbon which is obtained from the atmosphere. Over the age of the earth the levels of CO2 have dropped substantially as it gets sequestered into the earth. We are naturally approaching such low CO2 levels that are below what plant life needs. When we would reach this point is still speculative but range from a few tens of millions of years to perhaps a billion.	Near zero	Guaranteed	Human intervention through the burning of fossil fuels is likely to have delayed this event but eventually, left to itself, this will occur. Colonization of other planets or star systems would eliminate this risk.
Artificial Intelligence (AI)	The magnitude of the threat of advanced AI is unknown but draws sooner as AI technology continues to advance. This is an area of total speculation... will true AI even be possible? If possible, will it have the capability or desire to destroy the human population, or will they exist in harmony with us?	Medium probability.	Medium- however will likely occur sooner rather than later.	Human expansion to the Moon, Mars, other planets, and large world ships could reduce this threat. Migration to the Stars could eliminate this threat. A malignant AI would not likely arise in two places simultaneously- hence either the colony or the solar system would have a heads up and "pull the plug".
Plague	100% mortality from any disease (natural or artificial) are unlikely, but possible. Human curiosity or evil intent (see war) may engineer something that is much more deadly than what nature would have evolved. Even though extinction level plagues are unlikely, less deadly plagues are possible- plagues large enough to set back civilization.	Low probability for extinction, but high probability for serious plague. COVID may just have been a preliminary. Possible serious impact to human economic and social development.	Low probability for extinction, but high probability for a serious plague that will severely inhibit economic development.	Human expansion to the Moon, Mars, other planets, and large world ships will reduce this threat. Migration to the stars would eliminate this threat.
War	While even a nuclear war would likely not exterminate all people (especially as over the last few decades the number of nuclear weapons has been slashed) it is possible that this situation can change quickly (witness the Russian invasion of the Ukraine or if China invaded Taiwan).	Low probability for extinction- however would likely occur sooner rather than later and would seriously impact human economic and social development.	Low probability for extinction- however would likely occur sooner rather than later.	Human expansion to the Moon, Mars, other planets, and large world ships will reduce this threat. Migration to the stars would minimize this threat.
Alien Invasion	Speculative but cannot be ruled out. We have no idea what is out there (if anything) but there is no guarantee they are friendly. They may be an	Low probability. Without any evidence that other civilizations exist or have existed it is	Unknowns but probably Low Probability. The earth has been in existence for 4.5	Migration to the stars could reduce this threat.

	Advanced Alien AI that hates or fears life.	impossible to determine.	billion years and there is no evidence that it was ever visited.	
Depopulation	Demonstrated. Virtually without exception all advanced countries are depopulating. Assuming all countries eventually become advanced this phenomenon is likely to spread across the globe.	Low probability for extinction but High probability for extreme population reduction. This appears to be the widespread result of wealth, secularization and globalization.	High. It is occurring in all first world countries.	Uncertain as to whether this will occur worldwide. As technology advances it can be offset by artificial inseminated/ artificial womb. Human expansion to the planets and stars may prevent this sociological convergence by permitting diverse societies that encourage childbirth.
Environmental Catastrophe.	Environmental mass extinction caused by some sort of tipping point. This seems unlikely as what that tipping point would be is unknown. Fifty years ago, there were concerns about running out of resources and food, which turned out to be not true. In the 1970's there were concerns about an ice age. Now there are concerns about pollution (which by most measures is improving), or climate change shifts. The earth has gone through major climate changes before, including much higher CO2 levels and higher temperatures (including the melting of all glaciers) this seems to be a long-term challenge but is unlikely to be a species extinction event.	Low Probability- though climate changes are real and will have an impact on civilization, they are unlikely to be extinction level.	Low probability except those as caused by the ageing of the sun or meteor/comet impact.	Human expansion to the Moon, Mars, other planets, and large world ships as migration to the stars will eliminate this threat.

TABLE 18-1 POSSIBLE EXTINCTION EVENTS AND MITIGATION STRATEGIES

All these risks, except the growing/dying sun, are mitigated by a large multi-planet species restricted to our solar system. Going interstellar would mitigate all these risks.

Over the next century our astronomical tools will continue to grow in capabilities. We will identify more and more stars with planets and even start identifying the atmospheric composition of these planets. What happens if we identify possible life around one of these planets... perhaps an oxygen atmosphere or some other biomarker? Paradoxically this would simultaneously encourage exploration but may decrease the intent to colonize as some concerns would be that either the native life would be dangerous or toxic to colonists (a possibility) or that the earth organisms would be an invasive species and be deadly to the native plants (also a possibility). These fears, while certainly legitimate, I have always found slightly irrational and strangely anthropomorphic. If the earth organisms prove more durable that they would supplant the native organism's, from a Darwinian perspective wouldn't this be good? More legitimate is so called Back Contamination whereby an alien organism is brought back to the earth with negative consequences. However, all our discussion in this book has been about a one way, ten-thousand year voyage where we are not even considering a return. Forward contamination is possible but again, what is the concern? When exploring Mars there is the argument that earth to Mars contamination may make it harder to study the natural process on Mars- but again, realistically I don't

see the point. Discovery of life on Mars would be an important discovery but you would think that, if DNA based, it would show clear differences from earth organisms. Similarly, if not DNA based, it would be obviously non-earth based.

The bases for not contaminating a planet were laid out in the International Astronautical Federations VIIIth congress in Rome in 1956 and reiterated by the National Academy of Sciences (NAS) and the Committee on Space Research (COSPAR). In 1964 COSPAR issued Resolution 26 affirming that:

the search for extraterrestrial life is an important objective of space research, that the planet of Mars may offer the only feasible opportunity to conduct this search during the foreseeable future, that contamination of this planet would make such a search far more difficult and possibly even prevent for all time an unequivocal result, that all practical steps should be taken to ensure that Mars be not biologically contaminated until such time as this search has been satisfactorily carried out, and that cooperation in proper scheduling of experiments and use of adequate spacecraft sterilization techniques is required on the part of all deep space probe launching authorities to avoid such contamination.

This is a very narrow definition and is reasonable. As technology improves the ability to analyze alien life will continue to advance and the time required for research is likely to be shortened unless advanced life is found. However, the end results are that the discovery of life per say should not inhibit colonization for long.

Occasionally, there appears to be some very fuzzy thinking within the scientific community. Professor Charles Cockell, a professor of astrobiology and the University of Edinburgh Scotland made the following statement (David, 2013):

One ethical argument is that it says something about our species that we think about our actions elsewhere and attempt to mitigate our impact prior to establishing a permanent presence beyond the Earth. We might want to preserve some places in pristine condition for future generations. We may also want to protect unknown benefits that could potentially be gained from places in space that human activity has not altered.

The logic of this is beyond me. Preserve for future generations? Why? Are there any examples where we have missed out on things in the past because they were not kept “pristine”? This goes beyond navel gazing into the realm of superstition where the future is some clockwork mechanism that mankind can accidentally disturb. The fact that no examples can be pointed to is an example of the pseudo- mystic perspective of this approach. When would this restriction be lifted? Ten years, one hundred, one million? What is the unknown benefit? Are their magical properties associated with being pristine? The opposite argument could be easily made with far more justification- arbitrary and random prohibitions will make colonizing more difficult and perhaps impossible. The risks associated with this restriction on expansion increase the chance of species extinction.

Where are they?

The Fermi Paradox is summarized by the statement made by the Italian American physicist Enrico Fermi in the summer of 1950 where he asked over lunch the question of “where is everyone”? This statement grew out of the fact that there are so many stars, likely many planets, and the universe is so old that life, and many civilizations should have arisen throughout the galaxy many times over. If this is true and the civilizations have traveled to the stars, they should have been to the earth already. The question can even be extended to alien artifacts...if there are large space structures (like Dyson spheres or even large Buzzard ramjets) why can't we see them? As our instruments become more advanced large structures should become visible. We can already see individual stars in distant galaxies. Very large structures, like Dyson spheres, we would be able to see out to a few thousand light years. It is reasonable to speculate that a thousand years from now our engineering structures and presence in our solar system would be much more pronounced. What about a civilization 100,000 years more advanced? Wouldn't they be even easier to identify?

In 1961 the astronomer Dr Frank Drake proposed the famous Drake Equation to attempt to apply some rigor on how many intelligent civilizations exist right now. The equation he proposed was:

$$\text{EQUATION 18-1 } N = R_* x f_p x \eta_e x f_l x f_i x f_c x L$$

Where:

N = number of civilization in our galaxy with which communications might be possible

R_* = average rate of star formation per year in our galaxy

f_p = fraction of those stars that have planets

η_e = average number of planets that can support life per stars that have planets

f_l = fraction of planets that could support life and actually develop life at some point

f_i = fraction of planets that support life that actually develop intelligent life

f_c = fraction of civilizations that develop technology that releases detectable signs

L = length of time for which civilizations release detectable signs into space

The problem with this equation is that except for the R_* and more recently, the f_p terms, most of the terms are complete guesses. Most, if not all of the remaining terms may be quite small. With the advances in space telescopes, it is likely that we can start making better estimates of η_e over the next few decades.

Looking at the remaining terms there are many possible reasons for the lack of signs of any other intelligence:

- f_l term- we don't know what percentage of planets develop life. The belief is that life may not be too difficult to arise since it appeared on Earth within a billion years of the earth's formation (possibly within a few hundred million years). In other words, it may have appeared within the

first 10% of the current age of the earth. This is a good argument that life arises frequently but weakened by the fact we have a sample size of one.

- f_i term- Intelligent life may be so improbably to evolve that there never was any. An extension of this is that complicated organisms are rare. This may be a very small fraction. The Earth is in a fairly stable orbit around a stable star, even though it experienced a couple of global ice ages. Nonetheless, life persisted but took over 3 billion years from when life first evolved to develop advanced multicellular organisms. Higher organisms like land animals appeared around 500million years ago- or when the earth was nearly 90% of its current age. This indicates that to move from simple life to complex organisms is much more difficult than the formation of life itself. Will a planet's environment stay stable enough for long enough to permit life to evolve? To see how close of a risk this is, it is estimated that life will be extinct on earth within a few million to one billion years when CO2 levels will drop too low to support plant life.
- f_c term- here are many items that could result in a very small f_c .
 - o Even though they are intelligent, their communications, large, engineered structures and travel capabilities are not vastly greater than ours so have not been detected.
 - o Communication is not a priority, or their communications are all local. It is possible that as civilizations advance their communications become harder to detect. For instance, communications on earth are increasingly being done by fiber optic cable or very narrow laser beams. These will not get picked up by an alien civilization. Except for a few intentionally beamed radio signals to specific areas of the sky, normal earth radio signals will not travel far and will not be detectable. This is another case of a small f_c .
 - o Interstellar Travel is too difficult and is not, or rarely, done. We have seen in this book how hard it is. Perhaps the technology is not capable of making interstellar travel ever practical. If they didn't visit us and their engineering structures are small, we would never know they are there.
 - o Civilizations become inward focused and are not interested in Interstellar or large-scale space structures at all. We landed on the moon 60 years ago and have not made any progress in colonization since then. Many of the most advanced nations are depopulating. Perhaps the effort and rewards of expansion and exploration are not worth the effort and space is never conquered. Perhaps they have a ideological passivity to the material world.
 - o They are wary of other intelligence and keep themselves intentionally hidden. More aggressively they keep themselves hidden as they get ready to invade!
 - o They are here, we just do not see them. Perhaps they are microscopic and are here now, but their civilization and technology are so different we don't recognize them.
- L term- detectable intelligent life is short lived and there are currently none- or they are extremely distant. Whatever civilizations there were became extinct- possibly for one of the reasons we mentioned. In this case L would be small.

From a macro perspective, all planets with life eventually become extinct. All stars gradually grow brighter as they age, raising their planet's surface temperature. Eventually many planets will be melted down as their parent star inflates into a red giant and engulfs them. For planets that escape this fate they will still be blasted with enough radiation to make their surface molten. After this insult their parent star dies and the planet (what's left of it) will become an eternally frozen cinder.

The Fermi Paradox offers can offer some pessimistic conclusions to our interstellar colonization dreams:

- Intelligent life is rare and/or short lived.
- Interstellar Travel is too hard and has never (or rarely) been done by other civilizations.
- We are alone.

Expansion prevents stagnation

Why would we consider expanding from the Earth and eventually from our Solar System? This is a surprisingly hard question to answer, especially in the modern world where substantial segments of society think humans should minimize or even eliminate their exploitation of the natural world.

All civilizations eventually fail. Frequently they sow the seeds of their own destruction. Why this is so seems to be intrinsic to human nature. The causes of failure are varied. Some civilizations fail because of external factors in the form of conflict with another, usually more technologically advanced civilization. However, not all do. Some civilizations adapt quickly to changes and thrive. Witness Japan in the late 1800's where it quickly industrialized and adopted the new technologies that it saw in the West. Other countries, those less willing to adapt and revise their traditions, quickly get overcome or made irrelevant. For these civilizations the reason for failure is intrinsic to the culture. When facing an external threat or radically different worldview, they don't adapt quickly enough to meet the threat but become isolationist and inward looking.

Some civilizations seem to self-destruct from the inside. Some civilizations rise and fall in an endless cycle of revolution and cultural upheaval. Witness the Soviet Union and the communist revolution of 1917, and its failure again in 1989. The external threat of World War 1 pushed the already unstable nation into a revolution that wiped out the old system. Cynicism and changing values made traditional institutions including the Czar and church, lose credibility. The irony is that the communist revolution was, in large part, an intellectual movement- the Intelligentsia. The fact that many of the most educated members of society believed in such an awful idea shows that education does not lead to rational thought or improved critical thinking skills. The end result of this intellectual revolution was 70 years of worldwide catastrophe. This intelligentsia movement devastated the Soviet Union, causing things like the Ukrainian famine, creation of the Gulags, the widespread liquidation of people and even more traumatic wars the Soviets engaged in. Amazingly these bad ideas inspired equally flawed copies throughout the world, including China (up to 20 million died in a manmade famine), Latin America, Cambodia, Vietnam, large parts of Africa etc. Bad ideas are almost impossible to eliminate because they seem to appeal to basic weaknesses in human nature. In the 21st century Russia is trying (yet again) to reinvent itself but does not seem to be learning any lessons from the past.

Sometimes a civilization loses the unity of vision that once powered it. Like the tower of Babel, a cacophony of millions of voices but no direction- very much like entropy- always heading toward more and more fragmentation and loss of cohesive voice. These civilizations have so many voices that it becomes difficult to separate the good from the bad ideas and unifying vision gets lost. This may have contributed to the fall of Rome and is evident in many Western nations today.

I believe that there is widespread agreement on how to build a successful and prosperous civilization. Democracy, capitalism, high social trust, institutional transparency, minimal but clear rules and regulations, and a population with high critical thinking skills invariably lead to a wealthy and prosperous society. The Russian civilization (as well as many others) rarely address or prioritize these issues. Other societies are strong in some of these areas but disregard others. The most successful societies are the ones that are strong in all. It should be relatively simple for a country to address these issues but because of human weakness, this is rarely done.

We may be seeing human civilization failing on a planet wide scale. As humans get wealthier, they get less practical. Liberal Arts become dominant over science or engineering. The people that once valued free speech when their voice was not heard, now stifle it with Safe Spaces. Standards get relaxed and then eliminated. The educated get rewarded instead of the intelligent. The intelligentsia becomes dominated by over educated but mediocre individuals who value square filling, getting a degree, and voicing meaningless platitudes over intellectual inquiry, grit, and hard work. The cultures become more inward focused and more tribal- but also risk adverse and resistant to any sacrifice. This confusion and dumbing down can be seen in individual actions- where “educated” individuals can feel very passionate that Global Warming is the most urgent problem humans face but support the closing of a local Nuclear Power plant while boarding a plane to vacation in another country to help “find” themselves.

Without human precedence, a new threat has emerged- as civilizations get wealthier all nations see a substantial drop off in fertility rates- the number of children born drops off below replacement level. This is not a recipe for an outwardly expanding species. If it were not for immigration, virtually ALL advanced countries would be depopulating. The significance of this is truly stunning. Why do wealthy and educated people not reproduce? As wealth spreads across the world, it is very easy to project that within 300 years the human population will be very small- perhaps a few billion people.

In science fiction we see the same inward-looking trends. In the '30s, '40s, and '50's we saw a lot of adventure science fiction where new capabilities, and new inventions drove adventures and outward views. Now much of science fiction is inward facing, talking about social justice, gender flexibility, sexual liberation, drugs, body modifications and mind-bending simulations. As we get wealthier, the practical need for outward expansion drops off. Interestingly many of these social changes seemed to be predicted with disturbing accuracy by some of the oldest classics including *The Machine Stops* by EM Forster, *Brave New World* by Aldous Huxley, *1984* by George Orwell, and *Fahrenheit 451* by Ray Bradbury. All are different but capture key truths that we see being played out in front of us.

Another disturbing worldwide trend is toward globalism where individual cultures are driven to a uniform sameness. The early founders of the United States recognized this as a problem and developed a solution- states would have considerable flexibility in how they were run. It was recognized that only with differences can good and bad ideas be compared and compete. There are certain concepts that are clearly superior to others when running a civilization- social trust, efficient institutions, rational decision makers, institutional transparency, and an educated/intelligent and productive workforce, are all common goods. Nevertheless, how these goals are pursued and how effective they are implemented has a large impact. In 1900 the average Argentinian was as wealthy as the average American. By 2020 they were only a third. Many of the richest countries are poor in natural resources (Japan, Germany) and many poor countries are rich in natural resources (Nigeria, Venezuela, many middle eastern countries). Geography and natural resources do not drive success, culture does.

Diversity is not just a word. As the world becomes more “united” diversity of thought is likely to be discouraged. Certainly, some concepts should be universal- including fairness, hard work and integrity. But every country, every culture, should be free to choose their own path... some will choose well and some poor, but the decision must ultimately rest with them. Argentina is not alone in choosing poorly- most countries do and frequently, like Venezuela, do far worse than Argentina.

The United States over the last 100 years, has frequently chosen the correct path. But this is no sure thing, and the progress of the last couple of centuries can be undone quickly. We can easily be the next Russia, Venezuela or Argentina. Currently many government and societal trends appear to be headed in the wrong direction. We see massive government expenditures directed towards marginal projects and for political patronage. The United States government, over the last few years, has burdened future generation with trillions of debt. Eventually this will need to be paid- making our children and their children poorer.

NASA may be a microcosm of this future mediocrity. We see NASA unable to finish many large projects and spend billions while standing still. NASA is frequently a political tool and an employment agency that sometimes attracts people that are looking for secure, high paying jobs or careers – but not to conquer space. NASA is buffeted by political goals of employment and social goals like diversity. NASA is NOT focused on the conquest of space or even representing the United States. That is why we can spend \$20 billion on the Space Launch System over the last 10 years- with a single launch. We can spend \$10 billion (original budget \$830million) on the James Webb Space Telescope, and it take 18 years (instead of 8) to build and deploy. Meanwhile, we have seen Space X develop, primarily with their own money, the Falcon 9 which lowered the price to access space by 75% over traditional, government sponsored launch providers. Furthermore, the SpaceX Starship, bigger than the Saturn V and which started development only five years ago looks to be within an orbital launch attempt within the year. Just as important, conventional wisdom would have said building such a large rocket would involve multiple countries, and tens of billions of dollars- it would be “just too big for one nation”. Space X, a company that did not even exist 20 years ago, has proven the collective wisdom of the “intelligentsia” wrong.

We have many examples where collective wisdom is anything but. When NASA started talking about building a Space Station in the late 1980’s, it quickly morphed from the American Space Station Freedom to the International Space Station- supposedly because it would lower NASA’s costs and also tie us closer to other countries. It was framed as a program too big for one nation. This ignored the fact that working with other nations introduces inefficiencies of its own. Different standards, different languages, and the need now to coordinate between all these nations is tremendously wasteful. We may be able to justify the international nature of the space station by saying it served other purposes... of politics and international relations. However, from an economic and scientific point of view it could not be justified.

Colonization, whether in Musk’s vision of Mars, Bezos and O’Neil’s vision of large space stations, or our even more ambitious interstellar colonies, may help us to grow as a civilization and species even as the earth gets materially richer but spiritually poorer and more inward looking. In the modern world the simulated worlds of video games and movies and even with popular artwork are usually much more attractive than the dirty reality of conquering space. The percentage of people suitable and, perhaps just as challenging, desiring to colonize space is actually extremely small. Similarly, people who emigrated to America were not the dilettantes of the old world. They were the salt of the earth.

We have all heard the argument- why spend money on space when we have so many problems here? This is a willfully ignorant argument. We can spend hundreds of billions (and have) and we will never eliminate homelessness or poverty. Despite the government spending vast sums of money, homelessness and poverty, along with many of the other ills of society, are not amenable to money. They are much more intractable and related to mental issues and societal priorities. In the United States we spend far more money per student on education (adjusted for inflation) today than we did 20-30 years ago, and student performance is worse. We have smaller classes and more support staff and student performance still goes down. Clearly the money spent is not the issue.

What will it take to conquer space and eventually the stars? Daniel Boorstin, author of some 20 books, was also the 12th Librarian of Congress. He passed away February 28th 2004. In an obituary in the Economist, it stated:

“Mr. Boorstin believed strongly in American exceptionalism, but in his own distinctive way. America was not better, more virtuous or more progressive than other countries. It was unique because it was founded on pragmatism rather than ideology, and was forged into a nation by the effort and necessity of taming a wild continent.” (The Economist, 2004)

These are going to be the requirements for the men and woman who conquer space...

Summary and Conclusions

I wrote this book to see if it would be possible, and if possible, how hard to build a starship with 21st century technology. If possible, I wanted to see what it would look like and how it would function. I was continuously surprised at the challenges and came to the reluctant conclusion that while technologically possible, the industrial scope is far larger than I anticipated. If a major effort were expended, we could go to the stars in the 21st century but the active verb is MAJOR- especially if we target a velocity of 300kps. The industrial capabilities, in particular the need for tremendous amounts of power and the size of the MMD along with the associated mining requirements of distant asteroids or comets are intimidating and are only something that can be attempted toward the later part of this century.

I also decided, surprisingly, that governments may play a very small role in colonizing the stars. I see them as playing a useful role in developing the technology (mainly large lightweight fission reactors, mass driver technology, fusion power and high strength materials including carbon fiber or equivalent for solar sails) but I don't see them as playing much of a roll in actually funding the mission. Unlike SpaceX, world governments are too focused on social and political issues that their efforts become diluted. Furthermore, governments, funded by taxpayers, are understandably risk adverse and become very bureaucratic. Space exploration frequently requires the exact opposite of these traits. SpaceX is successful because one person with the support of a bunch of likeminded and committed individuals all have a clear vision. Governments frequently do not.

This book is also not an end-all- but was primarily written to satisfy my curiosity. It was my attempt to pull together a lot of technological options and assemble them into a starship that had the best chance of being built from the perspective of the third decade of the twenty-first century. Further engineering developments or new ideas may make this mission architecture and my proposed solutions obsolete.

This book was an attempt to simply answer the question- if we had to build a starship in this century, what is the most likely configuration based on today's state of engineering and technology?

Many of the issues that came up surprised me- things that I thought would be a minor problem turned out to be anything but. Conversely, I learned of some solutions that I never had an inkling of or would not have considered before I began.

I really enjoyed this voyage of discovery- and I hope you did too.

Appendixes

Appendix A- Scientific Notation, Conversion Factors

Scientific Notation and SI Prefixes

$1,000,000,000,000=10^{12}$	tera	T
$1,000,000,000=10^9$	giga	G
$1,000,000=10^6$	mega	M
$1,000=10^3$	kilo	k
$.01=10^{-2}$	centi	c
$.001=10^{-3}$	milli	m
$.000001=10^{-6}$	micro	μ
$.000000001=10^{-9}$	nano	n

Conversion Factors

1 kg= 2.21 pounds
1 Metric Ton= 1000kg= 2210pounds
1 Meter= 3.2808feet
1 Kilometer= .621 miles
1 Kilometer²= 247 Acres
1 Acre= 4047 m²
1 Astronomical Unit (AU)= 149,600,000 km
1 Light Year (LY)= 63,241 AU = 9.46×10^{12} km
1°C=1°K= 1.8°F
1 Atmosphere= 1.0132bar= 101325 kPa= 14.7psi
1 Pascal= 1N/m²
1 Watt= 1J/s

Appendix B- The Nearest Stars- Out to 16 LY

Star	Type System	Distance LY	Stellar Class	Mass (Sun=1)	Absolute Magnitude	Temperature	Stellar Stability	Planet Potential	Comments
Sun		8 min	G2V	1	4.85				
Proxima Centauri	Triple Star	4.2441	M5.5	.122	15.53	3042	Active Chromosphere	Possible	Possible planet in habitable zone; very dim star flare star
Alpha Centauri A	Triple Star	4.365	G2V	1.1	4.38	5790			Possible Target
Alpha Centauri B	Triple Star	4.365	K1V	.907	5.71	5260			Possible Target
Bernard Star		5.9577	M4	.144	13.22	3134K			To small
Wolf 359		7.856	M6	.090	16.55	2800			To small
Lalande 21185		8.307	M2	.39	10.44	3828		2 Possible	Potential; planets not in habitable zones
Sirius A/B	Double Star	8.659	A0/ White Dwarf	2.063/1.018	1.42/ 11.34	9940/ 25,000			Sirius is 25 times brighter than the sun- to receive the equivalent Solar Radiation you would need to be 5AU from Sirius
Luyten 726 A/B	Double Star	8.79	M5.5/ M6	.102/.100	15.40/ 15.85	2670/2650			To small
Ross 154		9.71	M3.5	.17	13.07	3340			Flare Star
Ross 248		10.31	M5.5	.136	14.79	2799			
Epsilon Eridani		10.8	K2	.82	6.19	5084			Prime Candidate
Lacaille 9352		10.72	M0	.486	7.34	3692			
Ross 128		11	M4	.168	13.51	3192			Planet detected that may be in the habitable zone
EZ Aquarii	Triple System	11.11	M5, M, M	.11/.11/.10	15.64/ 15.58/ 16.34				Two stars orbit very close; may be habitable zone
61 Cygni A/B	Binary	11.4	K5/K7	.70/.63	7.506/ 8.228	4526/4077			Widely Separated binary
Procyon	Binary	11.456	F5/White Dwarf	1.499/.602	2.66/13.0	6530/7740			Evolving into a Supergiant

Struve 2398									
Groombridge 34 (A/B)	Binary	11.62	M1.4/ M4.1	.38/.15	8.08/ 11.06	3607/3 304		2 planets	Two planets detected; neither in the habitable zone
DX Cancri									
Tau Ceti		11.8	G8.5	.783	5.69	5344		Several planets	Prime Candidate
Epsilon Indi		12.05	K5	.754	6.89	4649			One indicated planet far outside habitable zone
GJ 1061									
YZ Ceti									
Luyten's Star		12.36	M3.5	.26	11.94	3150		Possible 4 planets	One planet in habitable zone
Teegarden Star									
Kapteyn's Star									
Lacaille 8760									
Kruger 60									
Ross 614A/B	Binary				13.09/ 16.17		Flare Star		
Wolf 1061		14.05	11.93			3342K		2 Planets identified	Good Target
Gliese 1		14.17	10.35			3567K			Good Target
L1159-16		14.5843	14.03			3158K			
Gliese 674		14.8387	11.89	.35	11.06	3600K			Planet In eccentric orbit
Gliese 687		14.8401	M3.5	.4	10.89	3095K			Good Target
Gliese 876		15.25	M4	.37	11.81	3129K			
Groombridge 1618		15.8797	K7	.67	8.16	3970K	Flare Star		Good target
Gliese 412 A/B		15.983			10.34/ 16.05	3687/2 700K			
Gliese 832		16.1939			10.2	3620K			
40 Erandi	Triple system	16.26	K.5/DA 4/ M.5						Companions are white dwarf and red dwarf

Stellar Candidate Color Code	
	Strong Candidate
	Candidate
	Low Probability Candidate
	Not likely

TABLE 0-1

Appendix C- Selected Space Probes and Interstellar Spacecraft

Spacecraft	Destination/ Mission	Years Launched	Launch Mass (kg)	Instrument Mass (kg)	Power Supply	Comments
Ranger 6-9	Moon Impact	1964-1965	365.7		Solar Panels 200W	
Lunar Orbiter 1-5	Moon Orbit	1966-1967	385		Solar Panels 375W	
Surveyor 1-7	Moon Landing	1966-1968	1039/306 Landing		Solar Panels 85W	
Mariner 9	Mars Flyby	1971	998/559	68 (Ames Research Center, 1973)	Solar Panels 500W	
Mariner 10	Venus/Mercury Flyby	1973	503	78 (Ames Research Center, 1973, pp. 148-159)	Solar Panels 850W	
Viking 1/2	Mars Orbit and Landing	1975	3506 883 Orbiter 572 Lander	69 Orbiter 55Lander (Ames Research Center, 1973, pp. 260-285)	620W Solar Orbiter/ 70W RTG Lander	
Pioneer 10/11	Jupiter, Saturn Flyby	1972	259	28 (Ames Research Center, 1973, pp. 81-130)	155W RTG	Interstellar
Voyager 1/2	Jupiter, Saturn, Uranus, Neptune Flyby	1977	823/ 773 Dry	105	470W RTG	Interstellar
Galileo	Jupiter Orbit and Atmospheric Probe	1989	2560 1880 Orbiter/ 340 Probe	118 Orbiter 30 Probe	570W RTG	
Cassini	Saturn Orbit and Titan Lander	1997	5712 2125 Dry		885W RTG	
New Horizons	Jupiter, Pluto Flyby	2006	478 401 Dry	30	245W RTG	Interstellar
Dawn	Vesta Orbit, Ceres Orbit	2007	1218 747		10,000W Solar at Earth 1300W Ceres	Propulsion 3 NSTAR Ion Thrusters

TABLE 0-2 SELECTED SPACE PROBES AND INTERSTELLAR SPACECRAFT

Appendix D- Some Physical Constants and Properties

$$c = \text{Speed of Light} = 3.00 \times 10^8 \text{ meter/sec}$$

$$G = \text{Gravitational Constant} = 6.672 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$$

$$\mu_e = GM_e = 398,614 \text{ km}^3/\text{s}^2$$

$$M_e = \text{Mass of Earth} = 5.972 \times 10^{24} \text{ kg}$$

$$R_e = \text{Mean Radius of Earth} = 6.37 \times 10^6 \text{ meters}$$

$$\sigma = \text{Stefan - Boltzmann Constant} = 5.67 \times 10^{-8} \text{ W/m}^2 \text{K}^4$$

$$\text{Density Air (Dry, 20C, 1atm)} = 1.29 \text{ kg/m}^3$$

$$\text{Density Water (20C, 1atm)} = 1,000 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Absolute Zero} = 0^\circ \text{K (Kelvin)} = 273.15^\circ \text{C (Centigrade)} = -459.76^\circ \text{F (Fahrenheit)}$$

Appendix E- Properties of the Planets

	Mercury	Venus	Earth	Mars	Ceres	Jupiter	Saturn	Uranus	Neptune	Eris
Diameter (Earth=1)	.3830	.9499	1	.532	.0737	10.973	9.1402	3.9808	3.8647	.1825
Diameter (km)	4880	12,104	12,742	6779	939	139,822	116,464	25,362	49,244	2326
Mass (Earth=1)	.055	.815	1	.107	.00016	317.8	95.159	14.536	17.147	.0028
Mean Distance from Sun (AU)	.3871	.7233	1	1.524	2.77	5.2038	9.5826	19.1913	30.07	67.864
Orbital Period (Earth years)	.2408	.6152	1	1.881	4.6	11.862	29.457	84.1051	164.8	559.07
Orbital Eccentricity	.2056	.00677	.0167	.0934	.0785	.0489	.0565	.04717	.08678	.43607
Mean Orbital Velocity (kps)	47.36	35.02	29.78	24.07	17.9	13.07	9.68	6.80	5.43	3.434
Sidereal Rotation Period (in Earth Days)	58.646	(224.701)	1	1.026	9.1hrs					14.56 days
Inclination of Axis (deg)	2.04	2.64	23.44	25.19	4	1.303	2.485	97.77	28.32	44.04
Mean Surface Temperature C	67	464	14	-60						-231
Gravity (Earth=1)	.38	.904	1	.3794	.029	2.528	1.065	.886	1.14	.084
Escape Velocity (kps)	4.25	10.36	11.19	5.027	.51	59.5	35.5	21.3	23.5	1.38
Mean Density (Water=1)	5.427	5.243	5.514	3.9335	2.162	1.326	.687	1.27	1.638	2.43
Number of Moons	0	0	1	2	0	80+	83+	27+	14+	1

TABLE 0-3 PLANET AND DWARF PLANET DATA TABLE

Appendix F- Summary of Design

	Launch Mass Mo (t)	Empty Mass (t)	Mass Fraction	Specific Impulse	Exhaust Velocity (kps)	Final Startship Velocity (kps)	Type of Engine	Power	Dimensions	Mission Duration	Years to go 10LY	Comments
Saturn V- Apollo	2,970	140	21.2	304/421	2.98/4.13	10.0	RP-1/LOX; LH/LOX	Fuel Cells; 1.5kw		2 weeks	300,000	3 Stage; Limited power/storage
	2,970	30	99.0	304/421	2.98/4.13	13.0	RP-1/LOX; LH/LOX	Fuel Cells; 1.5kw		2 weeks	230,769	3 Stage
Saturn VB- Skylab	3,000	140	21.4	304/421	2.98/4.13	9.0	RP-1/LOX; LH/LOX	Fuel Cells; 8kw		80 weeks	333,333	2 Stage
Starship- 2 Stage	5,200	200	26.0	380	3.7	11.6	Methalox	Fuel Cells/Solar		126 weeks	258,621	
Starship- 1 Stage	1,400	200	7.0	380	3.7	7.3	Methalox	Fuel Cells/Solar		126 weeks	410,959	
StarshipPlus- 1 Stage	4,000	200	20.0	380	3.7	11.2	Methalox	Fuel Cells/Solar		126 weeks	267,857	
Saturn VI	3,000	150	20.0	452	4.4	13.3	LH/LOX	Fuel Cells/ RTG; 5kw		19 Years	225,564	
Saturn VI with Jupiter Slingshot	3,000	150	20.0	452	4.4	25.0	LH/LOX	Fuel Cells/ RTG; 5kw		19 Years	120,000	Add dV 5kps from a small Jupiter Slingshot and leveraging Earths orbital velocity
Saturn VIIA	3,000	150	20.0	900	8.8	50.0	Nuclear Thermal	Sterling; 5kw	42.8m LH Tank	11 years	60,000	Jupiter Powered Manuever of dV 14kps
Saturn VIIIB	3,000	150	20.0	4200	41.2	120.0	Electric Ion- NEXT Engine	Sterling/35kw/ Americum		11 years manned; 250 years unmanne d		Theoretical velocity; because of gravity losses will be much less; Engine will need to operate for 4500 years
Saturn VIIC	3,000	20 NA		900/ 4200	40/97	13	Nuclear Thermal/ Electric Ion- NEXT Engine	Sterling/35kw/ Americum	41.9m LH Tank; 4.9m Xenon	250 years unmanne d	21,898	Two Stage; powered maneuver around Jupiter; workable; only 20mt empty final stage; Stage 1- 40kps, Stage 2- 97kps
Saturn VIIIA	3,000	150	20.0	1000	9.8	90.0	Nuclear Thermal	Fission			33,333	10radii Solar Powered Manuever
Saturn VIIIA Aggressive	3,000	150	20.0	1000	9.8	120.0	Nuclear Thermal	Fission			25,000	3 Radii Solar Powered Manuever
Saturn VIIIB	3,000	150	20.0	5000	49.1	147.2	Electric Ion- VASMIR	Fission; KRUSTY Equivalent; 200kw			20,387	Theoretical velocity; because of gravity losses will be much less; Engine will operate for 822 years
Saturn VIIIC	3,000	20 NA		5000	49.1	300.0	Nuclear Thermal/ Electric Ion HIPEP	Fission- KRUSTY equivalent; 200kw	41.9m LH Tank; 4.9m Xenon		10,000	Two Stage; powered maneuver around Sun; workable; only 20mt empty final stage; Stage 1- 85kps, Stage 2- 220kps
Saturn IXA	3,000	150	20.0	6000	58.9	176.6	Electric Ion/MPDT	Beamed/ Fission			16,989	50N; 2MW
Saturn IXB	3,000	150	20.0	9600	94.2	282.5	Electric Ion/HIPEP	Beamed/ Fission			10,618	54N; 80 HIPEP; 3.2MW; Power plant will weigh more than our m1
Saturn IXC	3,000	150	20.0	NA	?		Solar Sail	Beamed/ Fission				Depends on lightness ratio Low mass of starship prevents this from being viable
Saturn IXD	3,000	150	20.0	100	1.0	3.0	Mass Driver	Fission			1,000,000	
Saturn XA	300,000	750	400.0	10000	98.1	300.0	Electric/ Ion	Advanced Fission			10,000	May not escape the suns gravity; 19000 years of acceleration/ deceleration
Saturn XB	30,000	3,000	10.0	10,000	98.1	230.0	Ion	Advanced Fission			13,043	Will have difficulty escaping suns gravity; Enroute Refueling
Saturn XC	30,000	1,500		1,000/ 10,000		300.0	Nuclear Thermal/Ion Engine	Advanced Fission			10,000	3 Stage; Enroute Refueling
Saturn C	4,000,000	200,000	20.0	1000/ 100	9.8/98	300.0	Nuclear/ Mass Driver	Advanced Fission	Torii 402m dia; MD 50km	10,000	10,000	Asteroid redirect; 3 Stage; Enroute Refueling

TABLE 0-4- SUMMARY OF DESIGN AND PERFORMANCE

Appendix G- Suggested Further Reading

Heppenheimer, T.A., (1977), Colonies in Space, Harrisburg, Stackpole Books

Johnson, Richard D; Holbrow, Charles (1977), Space Settlements: A Design Study, Honolulu, University Press of the Pacific

Long, K. F., (2012), Deep Space Propulsion: A Road to Interstellar Spaceflight, New York, Springer

Mallove, Eugene; Matloff, Gregory, (1989), The Starflight Handbook: A Pioneer Guide to Interstellar Travel, New York, John Wiley and Sons

Mauldin, John H. (1992), Prospects for Interstellar Travel, Vol 80. San Diego, Univelt, Incorporated,

Sutton, George P; Biblarz, Oscar, (2001), Rocket Propulsion Elements- Seventh Edition, New York, John Wiley & Sons, Inc

Taylor, Travis S, (2017), Introduction to Rocket Science and Engineering, Boca Raton, CRC Press, Taylor & Francis Group

Bibliography

- Ad Astra Rocket. (n.d.). *Our Engine*. Retrieved from Ad Astra Website:
<https://www.adastrarocket.com/our-engine/>
- Aerojet Rocketdyne. (n.d.). *RS-25 Engine*. Retrieved from Aerojet Rocketdyne:
<https://www.rocket.com/space/liquid-engines/rs-25-engine>
- Ames Research Center. (1973). *Science Instrument Survey*. Moffet Field, California: National Aeronautics and Space Administration Ames Research Center.
- Andres, M. C., & Nikolai, T. (2011). The VASIRM Engine: Benefits, Drawback, and Technological Challenges. *The 32nd International Electric Propulsion Conference* (p. 8). Wiesbaden, Germany: IEPC.
- Andres, M. C., & Nikolay, T. (2011). The VASIMR Engine: Benefits, Drawbacks, and Technological Challenges. *32nd International Electric Propulsion Conference* (p. 8). Wiesbaden: International Space University.
- Arnold, W. H., Bowen, S., Fine, K., Kolm, M., Kolm, H., Newman, J., . . . Snow, W. R. (1979). Space Resource and Space Settlements. In G. K. O'Neill (Ed.), (pp. III-1). Retrieved from National Space Society: <https://space.nss.org/settlement/nasa/spaceres/toc.html>
- Asker, J. R. (1991). Particle Bed Reactor Central to SDI Nuclear Rocket Project. *Aviation Week and Space Technology*, 18-19.
- Bhutada, G. (2021, October 5). *All the Metals We Mined in One Visualization*. Retrieved from Visual Capitalist: <https://www.visualcapitalist.com/all-the-metals-we-mined-in-one-visualization/>
- BOEING. (2018, October 12). *Boeing Space*. Retrieved from twitter:
<https://twitter.com/BoeingSpace/status/1050790346517549059/photo/1>
- Bottke, W. J., Durda, D., Nesvorny, D., Jedicke, R., Morbidelli, A., Vokrouhlicky, D., & Levison, H. (2005, March 14). The Fossilized Size Distribution of the Main Asteroid Belt. *Icarus*, p. 115.
- Bryce Space and Technology. (2019). *The Annual Compendium of Commercial Space Transportation: 2019*. Retrieved from Bryce Tech: <https://brycetek.com/>
- Catling, D. C., & Zahnle, K. J. (n.d.). The Planetary Air Leak. *Scientific American*.
- Charifoulline, Z. (2006). Residual Resistivity Ratio (RRR) measurements of LHC Superconducting NbTi cable strands. *IEEE Transactions on Applied Superconductivity*, 1188-1191.
- Choueiri, E. Y. (2009, February). New Dawn for Electric Rockets. *Scientific American*, p. 64.
- Christiansen, E. L. (2003). *Meteoroid/Debris Shielding TP-2003-210788*. Houston Texas: Lyndon B Johnson Space Center.
- Clark, J. D. (1972). *Ignition! An Informal History of Liquid Rocket Propellant*. New Brunswick: Rutgers.

- Cmglee. (2017, March 25). *Wikipedia Commons*. Retrieved from Wikipedial Commons:
<https://commons.wikimedia.org/w/index.php?curid=31761437>
- Cornmell, J. (2021, Dec). *Stellar Map- Location of the Stars with Potentially Habitable Exoplanets*. Retrieved from PHL@Aricibo: <https://phl.upr.edu/projects/habitable-exoplanets-catalog>
- David, L. (2013, January 17). *'Planetary Parks' Could Protect Space Wilderness*. Retrieved from Space.com: <https://www.space.com/19302-planetary-parks-space-wilderness-protection.html>
- Delsanti, A. a. (2006). *The Solar System Beyond the Planets*. *Institute for Astronomy*, 11.
- Dietzler, D. (2021). *Chemistry for Spacer Settlement*. David A Dietzler.
- Doty, R., & Garcia, M. (. (2021, Feb 25). *New Brine Processor Increases Water Recycling on International Space Station*. Retrieved from NASA: <https://www.nasa.gov/feature/new-brine-processor-increases-water-recycling-on-international-space-station>
- Dyson, G. (2002). *Project Orion: the True Story of the Atomic Starship*. New York: Henry Holt and Company.
- Eddy, J. (1979). *SP-402A A New Sun: The Solar Results from Skylab pg 2*. (R. Ise, Editor) Retrieved from NASA: <https://history.nasa.gov/SP-402/p2.htm>
- ESA. (2019, September 1). *Gaia Summary*. Retrieved from European Space Agency: <https://sci.esa.int/web/gaia/-/28820-summary>
- Etchegaray, M. I. (1987). *Preliminary Scienttific Rational for a Voyage to a Thousand Astronomical Units*. Pasadena, California: NASA Jet Propulsion Laboratory.
- Everyday Astronaut. (2022, July 14). *Raptor 1 VS Raptor 2: What's New//What's Different*. Retrieved 8 11, 2022, from Youtube: https://www.youtube.com/watch?v=ALiNmzoo1_E
- Fung, M. (2005). *Energy Density of Hydrogen*. Retrieved from The Physics Factbook- An Encyclopedia of Scientific Essays: <https://hypertextbook.com/facts/2005/MichelleFung.shtml>
- Garner, C. E., Rayman, M. M., Brophy, J. R., & Mikes, S. C. (2013). *Ion Propulsionj: An Enabling Technology for the Dawn Mission*. Pasadena : Jet Propulsion Laboratory, National Aeronautics and Space Administration.
- Gerrish, H. P. (2016, February 3). *Solar Thermal Propulsion at MSFC*. Retrieved from Nasa Technical Reports Server: <https://ntrs.nasa.gov/api/citations/20160003173/downloads/20160003173.pdf>
- Giambusso, M., Diaz, F. R., Corrigan, A. M., Dean, L., & Warrayat, M. F. (2021, December). *Technical Papers 2021 Archives*. Retrieved from Ad Astra: https://www.adastrarocket.com/wp-content/uploads/2021/12/2021_AIAA_ASCEND_VASIMR.pdf
- Giovanni Vulpetti, L. J. (2008). *Solar Sails: A Novel Approach to Insterstellar Travel*. New York: Copernicus Books Springer Science.
- Glenn Research Center. (n.d.). *Magnetoplasmadynamic Thrusters*. Retrieved 2022, from Nasa Glenn Research Center.

- Globus, A. (2017). Space Settlement Population Rotation Tolerance. 19.
- Globus, A. (April 2017). Orbital Space Settlement Radiation Shielding. *NSS Journal of Space Settlement*, 19.
- Gregersen, E. (2019, September 18). *Very Large Telescope*. Retrieved from Encyclopedia Britannica: <https://www.britannica.com/topic/Very-Large-Telescope>
- Grevesse, N., & Sauval, A. J. (1986-1987). *CRC Handbook of Chemistry and Physics Rev 85*, 161. Boca Raton, FL.
- Hall, T. W. (1997). Artificial Gravity and the Architecture of Habitats. *International Symposium on Space Tourism*. Bremen: Department of Architecture, Chinese University of Hong Kong. Retrieved from http://www.spacefuture.com/archive/artificial_gravity_and_the_architecture_of_orbital_habitats.shtml
- Harman, C. (n.d.). Retrieved from <http://sites.psu.edu/ceh5286/images/>
- Haslett, R. (1995). *Space Nuclear Thermal Project Propulsion Final Report*. Phillips Laboratory Air Force Material Command. Bethpage: Grumman Aerospace Corporation.
- Hatfield, M. (2018, Nov 18). *To Image the Leaky Atmosphere, NASA Rocket Team Heads North*. Retrieved from NASA Goddard Sounding Rockets: <https://www.nasa.gov/feature/goddard/2018/to-image-leaky-atmosphere-nasa-rocket-team-heads-north>
- Heacock, R. (1980). The Voyager Spacecraft. *The Institution of Mechanical Engineers*, (p. 219). London.
- Henson, K. a. (1977, June). *L5 News*. Retrieved from National Space Society: <http://www.nss.org/settlement/L5news/L5news/L5news7706.pdf>
- Heppenheimer, T. A. (1977). *Colonies in Space*. Harrisburg: Stackpole Books.
- Herman, D. A., Tofil, T. A., Santiago, W., Kanhaw, H., Polk, J. E., Hofer, R. R., . . . Allen, M. (2018). Overview of the Development and Mission Application of the Advanced Electric Propulsion System (AEPS). *35th International Electric Propulsion Conference* (p. 6). Atlanta: NASA Glenn Research Center.
- Historic Spacecraft. (n.d.). *International Space Station*. Retrieved from Historic Spacecraft: https://historicspacecraft.com/Diagrams/S/ISS_Size_Comparison_1200x700_RK2016.jpg
- Jenkins, D. R. (2012). *Space Shuttle: The History of the National Space Transportation System- The First 100 missions*. North Branch, MN: Specialty Press.
- Johnson, R. D., & Hobrow, C. e. (1977). *Space Settlements: A Design Study*. NASA.
- Johnson, R. D., & Holbrow, C. (1977). *Space Settlements: A Design Study*. Honolulu: University Press of the Pacific.
- Juhasz, A. J. (2001, January). *An Analysis and Procedure for Determining Space Environmental Sink Temperatures with Selected Computational Results*. NASA.

- Kaye, G. a. (1995). 3.1.3 *Abundances of Elements*. Retrieved from National Physical Laboratory Kay and Laby Table of Physical and Chemical Constants :
https://web.archive.org/web/20190518224615/http://www.kayelaby.npl.co.uk/chemistry/3_1/3_1_3.html
- Kelvey, J. (2023). Nuclear Rocket Redux. *Aerospace America*, 37.
- Kelvey, J. (2023, April). The Harshest Reality. *Aerospace America*, 36.
- Kolm, H. (1980, Septuember). *L5 News: Mass Driver Update*. Retrieved from National Space Society:
<https://space.nss.org/l5-news-mass-driver-update/>
- Kolm, H., Fine, K., Williams, F., & Mongeau, P. (1980). *Practical Coilgun Design*. Retrieved from Basic Ideas; Overview of Electromagnetic Guns:
<http://www.coilgun.info/theorymath/electroguns.htm>
- Lada, C. J. (2006). Stellar Multiplicity aand the IMF: Most Stars are Single. *Astrophysical Journal Letters*, pp. 640, L63-L66. Retrieved from
https://lweb.cfa.harvard.edu/~clada/pubs_html/pubs/binaries_final.pdf
- Lewandowski, E. J., Dobbs, M. W., & Oriti, S. M. (2016). *Advanced Stirling Radioisotope Generator Engineering Unit 2 Anomaly Investigation*. Cleveland: NASA Glenn Research Center.
- Lodders, O. f. (2007, September 9). *Solar System Abundances*. Retrieved from Wikipedia Commons:
<https://en.wikipedia.org/wiki/File:SolarSystemAbundances.jpg>
- Ludwig, R., & Taylor, J. (2002). Article 4: Voyager Telecommunications. *DESCANSO Design and Performance Summary Series*.
- Lyons, V. J., Gonzalez, G. A., Houts, M. G., Iannello, C. J., Scott, J. H., & Surampudi, S. (2012). *Space Power and Energy Storage Roadmap Technology Area 03*. NASA. Retrieved from
https://www.nasa.gov/pdf/501328main_TA03-ID_rev7_NRC_wTASR.pdf
- Lyons, V., Gonzalez, G. A., Houts, M. G., Iannello, C. J., Scott, J. H., & Surampudi, S. (2010). *Draft Space Power and Energy Roadmap Technology Area 3*. Nasa.
- Mansfield, C. L. (2006, July 26). *International Space Station*. Retrieved from NASA:
https://www.nasa.gov/mission_pages/station/behindscenes/truss_segment.html
- Morber, J. (2018, August 23). *Should We Study Human Embryos Beyond 14 Days?* Retrieved from PBS Social: <https://www.pbs.org/wgbh/nova/article/14-day-rule/>
- Morbidelli, A. (2005, Dec 9). Origin and Dynamical Evolution of Comets and their Reservoirs. *Lecture Notes*.
- NASA. (1991, Jul). *Living in Space*. Retrieved from
https://www.nasa.gov/pdf/146558main_RecyclingEDA%28final%29%204_10_06.pdf.
- NASA. (2022, April 30). *Exoplanet Catalog*. Retrieved from NASA Exoplanet Exploration:
<https://exoplanets.nasa.gov/discovery/exoplanet-catalog/>

- NASA Associate Deputy Administrator for Policy. (2011). *Falcon 9 Launch Vehicle NAFCOM Cost Estimates*. NASA. Retrieved from https://www.nasa.gov/pdf/586023main_8-3-11_NAFCOM.pdf
- Nasa Glenn Research Center. (2004, November). *Magnetoplasmdynamic Thruster Fact Sheet FS-2004-11-022-GRC*. Retrieved from Glenn Research Center: https://www.nasa.gov/centers/glenn/pdf/105909main_FS-2004-11-022.pdf
- NASA. (n.d.). *Glenn Research Cetner Fact Sheet Magnetoplasmdynamic Thrusters*. Retrieved from NASA: <https://www.nasa.gov/centers/glenn/about/fs22grc.html>
- NASA/JPL- Caltech/R. Hurt. (2017, November 8). *Solar System Exploration*. Retrieved from NASA Science: <https://solarsystem.nasa.gov/resources/285/the-milky-way-galaxy/>
- Northon, K. e. (2015, November 5). *Press Release - NASA Mission Reveals Speed of Solar Wind Stripping Martian Atmosphere*. Retrieved from NASA: <https://www.nasa.gov/press-release/nasa-mission-reveals-speed-of-solar-wind-stripping-martian-atmosphere>
- Norton, O. R. (2002). *The Cambridge Encyclopedia of Meteorites*. Cambridge: Cambridge University Press.
- Nuclear Power*. (n.d.). Retrieved from Nuclear Power: <https://www.nuclear-power.com/nuclear-power-plant/nuclear-fuel/fuel-consumption-of-conventional-reactor/natural-uranium-consumption/>
- O'Callaghan, J., & Kremer, K. (2012, October 12). *Do they "make" Oxygen to breath on the ISS*. Retrieved from Space Answers: <https://www.spaceanswers.com/space-exploration/do-they-make-oxygen-to-breathe-on-the-iss/>
- Office of Nuclear Energy. (n.d.). *Nuclear 101: How Does a Nuclear Reactor Work*. Retrieved from Office of Nuclear Energy: <https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work>
- Orloff, R. W. (2004, September). *National Aeronautics and Space Administration NASA History Division*. Retrieved from Apollo By the Numbers A Statistical Reference NASA SP-2000-4029: https://history.nasa.gov/SP-4029/Apollo_18-20_Ascent_Data.htm
- Polk, J. E., Kakuda, R. Y., Anderson, J., & Brophy, J. (2000). Inflight Performance of the NSTAR Ion Propulsion System on Deep Space One Mission. *IEEE Aerospace Conference Proceedings* (p. 2). NASA Glenn Reasearch Center.
- Powell, C. S. (2018, Aug 13). *How Many Humand Would It Take to Keep Our Species Alive*. Retrieved from NBC News MACH: <https://www.nbcnews.com/mach/science/how-many-humans-would-it-take-keep-our-species-alive-ncna900151#anchor-strongAstrategyagainstextinctionstrong>
- Presby, A. L. (2004, December). Thermophotovoltaic Energy Conversion in Space Nuclear Reactor Power Systems. *Masters Thesis*. Monterey, CA, USA: Naval Postgraduate School.
- Ragheb, M. (2021, June 21). *Nuclear Marine Propulsion*. Retrieved from Dr Magedi Ragheb: <https://mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Nuclear%20Marine%20Propulsion.pdf>
- Reim, G. (2022, November 7-20). Laser Power. *Aviation Week and Space Technology*, p. 49.

- Roberts, T. G. (2019). *Comparing Costs for Space Launch Vehicles*. Retrieved from CSIS Aerospace Security Project: <https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/>
- Siegel, E. (2018, Dec 13). *Science- NASA Doesn't Have Enough Nuclear Fuel for Its Deep Space Missions*. Retrieved from <https://www.forbes.com/sites/startswithabang/2018/12/13/nasa-doesnt-have-enough-nuclear-fuel-for-its-deep-space-missions/?sh=662c59e51c18>:
<https://www.forbes.com/sites/startswithabang/2018/12/13/nasa-doesnt-have-enough-nuclear-fuel-for-its-deep-space-missions/?sh=662c59e51c18>
- Silvera, I. F., & Cole, J. W. (2009). Metallic Hydrogen: The Most Powerful Rocket Fuel Yet to Exist. *Journal of Physics: Conference Series*. Tokyo.
- Singer, C. E. (1979). *Interstellar Propulsion Using a Pellet Stream for Momentum Transfer*. Princeton: Princeton University.
- Solar Physics- The Solar Interior*. (n.d.). Retrieved from National Aeronautics and Space Administration Marshall Space Flight Center: <https://solarscience.msfc.nasa.gov/interior.shtml>
- Spaceflight 101. (2022). *SpaceX Raptor*. Retrieved from Spaceflight 101: <https://spaceflight101.com/spx/spacex-raptor/>
- Spin Launch. (n.d.). *Spin Launch*. Retrieved from Spin Launch Web site: <https://www.spinlaunch.com/orbital#p2>
- Stenger, R. (2002, March 9). *Report: Make Deep Space Travel a Family Affair*. Retrieved from CNN Space: <http://www.cnn.com/2002/TECH/space/03/09/family.spacetravel/>
- Stuhlinger, L. B. (1973). *EP-107 Skylab: A Guidebook*. NASA.
- Sutton, G. P., & Biblarz, O. (2001). *Rocket Propulsion Elements Seventh Edition*. New York: John Wiley & Sons Inc.
- Sviatsolavsky, I. (1993). *The Challenge of Mining He-3 on the Lunar Surface: How All the Parts Fit Together*. Wisconsin Center for Space Automation and Robotics.
- Taylor, J., Sakamoto, L., & Wong, C.-J. (2002). Cassini Orbiter/Huygens Probe Telecommunications. *DESANCO Design and Performance Summary*, 18.
- Taylor, S. R. (1975). *Lunar Science: a Post-Apollo View*. New York: Oxford: Pergamon Press.
- The Economist. (2004, March 18). Daniel Boorstin. *The Economist*.
- The Empire State Building. (n.d.). *Empire State Fact Sheet*. Retrieved from The Empire State Building: [extension://elhekieabhbkmcefcobjddigjcaadp/https://www.esbnyc.com/sites/default/files/esb_fact_sheet_4_9_14_4.pdf](https://www.esbnyc.com/sites/default/files/esb_fact_sheet_4_9_14_4.pdf)
- Vacuum Vessel*. (Retrieved August 10, 2024). Retrieved from ITER: <https://www.iter.org/mach/VacuumVessel>

- Valleynewslive. (2010, Aug 6). Retrieved from Valleynewsslive.com:
http://valleynewslive.tv/info/info_tower.html
- Wang, B. (2019, December 10). *SpaceX Starlink Satellites Could Cost \$250,000 Each and Falcon Costs Less than \$30 Million*. Retrieved from Next Big Future:
<https://www.nextbigfuture.com/2019/12/spacex-starlink-satellites-cost-well-below-500000-each-and-falcon-9-launches-less-than-30-million.html>
- Weissman, P. R. (1983). The Mass of the Oort Cloud. *Astronomy and Astrophysics*, 90-94.
- Whipple, F. L. (1947). Meteorites and Space Travel. *The Astronomical Journal*, Vol 52, 131.
- Woods, W. D. (2008). *How Apollo Flew to the Moon*. New York: Springer.
- Woods, W. D. (2011). *How Apollo Flew to the Moon*. New York: Springer.
- Woolfson, M. (2000). The origin and evolution of the solar system. *Astronomy and Geophysics*, Vol 41, Issue 1, Pages 1.12-1.19.
- World Bank. (2016). *Solid Waste Management*. Retrieved from World Bank:
<https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management>
- World Nuclear Association. (2022, July). *World Uranium Mining Production*. Retrieved from World Nuclear Association: <https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx>
- Yampolskiy, R. V. (2018). *Minimum Viable Human Population with Intelligent Interventions*. Computer Engineering and Computer Science Speed School of Engineering, University of Louisville.
- Yeoman, D. (n.d.). *Jet Propulsion Laboratory California Institute of Technology*. Retrieved from Herschel Space Observatory: <https://herschel.jpl.nasa.gov/solarSystem.shtml>
- Yu, M.-F., Lourie, O., Dyer, M. J., Moloni, K., Kelly, T. F., & Ruoff, R. S. (2000, January). Strength and Breaking Mechanism of Multiwalled Carbon Nanotubes Under Tensile Load. *Science*, p. 637.
- Zubrin, R. (2023). *The Case for Nukes*. Lakewood: Polaris Books.
- Zubrin, R. (1991). Nuclear Salt Water Rockets: High Thrust at 10000 sec ISP. *Journal of The British Interplanetary Society*, 2.

About the Author

David W McGuire is a retired Colonel from the USAF and AF Reserve where he held various jobs as an Acquisition and Procurement Officer, C-5 Maintenance Officer, Maintenance Squadron Commander and Deputy Group Commander. He also has worked in the chemical, pipeline and petroleum industries where he held varied positions including Terminal Manager, Regional Accountant Manager, Regional Engineering Manager, and Regional Operations Director. He has a degree in Aerospace Engineering and an MBA.