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The Conquest of Space:

Handbook for Space Infrastructure for the 21st and 22nd Century

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Contents

Introduction

I frequently like to picture myself as some advanced and impartial alien observing the earth. They would be cool and logical, rational and practical. They would see things as they are.

A few years ago, while performing this ritual, I asked myself, in the first couple of decades of the 21st century, what revolutionary economic and technical changes have occurred? To make the list it has to have moved the needle- created billions of dollars in economic growth with millions of jobs, possibly created a new industry and have worldwide impact. Steam would have been such an invention. Electricity, the car, the airplane. In the 1970's and 1980's it might have been the green revolution with the development of GMOs that helped to feed the world. In the 80's and 90's the explosion of consumer electronics.

In the 1990's and early 2000's I would have said it was the logistics revolution with growth of Amazon and the delivery of massive volumes of packages which radically changed the way we shop and ultimately eliminated many traditional stores.

What have these developments been in the 21st century? Grudgingly I might include the iPhone. My hesitation with this is that this development was coming, and while it impressively pulled together diverse electronics and a lot of different technologies, most already existed and an iPhone type device would have been developed within a couple of years by others. The main technology driving many of the electronic industries capabilities was the event of massive and rapidly assessable memory and this was, and continues to be a large driving trend in improvement. Most of the iphones components and their associated technology are made by companies scattered around the world. Apple did a tremendous job of pulling all these capabilities together and was superb in developing their operating system, but within a couple of years other companies, frequently sourcing from similar or the same factories, were building Apple like phones.

For the 21st century I came up with only three radical and new developments, and all were from the United States:

- Fracking
- Tesla
- SpaceX

The impact of Fracking cannot be overstated. It has extended the duration of low-price gas and oil for the last 20 years. It prevented the United States from having an even worse trade deficit by eliminating most oil imports. It weakened many authoritarian regimes including Russia, Venezuela and many middle eastern countries. Currently most gas and oil in the United States comes from Fracking, and the US produces almost 40% more energy than it did in 2005. Cheap energy is one of the primary reasons that inflation has been moderate for most of the last 25 years (Chinese manufacturing is the other). Fracking was a technology that was applied at small scale since the 1940's. No one in the year 2000 would have realized that fracking would produce annually ten's of billions of revenue, make the United States the worlds biggest oil and gas producer, reshape the global economy, and extend oil reserves by many decades.

Before Tesla, electric cars had been built but never caught on in a large-scale way. Within a few years of its founding Tesla created the first practical electric car, built a large charging network, and followed up with three more designs that expanded the vehicle line up. They were the first successful new car company in the United States in over 100 years and created a whole new industry of competitors who adapted their technology. They became the most valuable car company in the world within less than twenty years of founding with about $100 billion in annual revenue.

SpaceX is another radical technology and industrial company. As with Tesla, within 20 years they developed a company from scratch that built rockets and rocket engines, cut launch prices from 75-90% over traditional launchers, and now account for about 80% of payload mass launched into orbit every year for the entire world. They built a satellite communications network of thousands of satellites which is rapidly expanding. This satellite network provides broadband access for marine vessels, aircraft and homes in areas where traditional 4G and 5G may be unavailable. SpaceX is privately held but recent private market valuation placed its value at $350 billion, meaning that it is the most valuable aerospace company in the world, exceeding GE, RTX, Airbus and Boeing. Some estimates put the value of SpaceX at $1.5 trillion.

Reusable or partially reusable rocket launchers were in place and discussed for the last fifty years and usually consisted of massive government developed projects that looked like spaceplanes. The Space Shuttle, though a marvel of engineering, cost about $500 million per launch. And this was the governments “reusable” program. The reasons why governments fail will be touched on later in this book but the reality is governments primary job is not to develop and make a nation stronger, but for the bureaucracy to survive. Getting launch costs down was a dream that was always a decade away with no firm idea how to accomplish it. Electric cars were built and discussed for over a century, but never came to fruition. A new car manufacturer in the United States (let alone one that would become the biggest) was never anticipated. And Fracking gas and oil was not something the government ever subsidized or expected.

My point, which I will revisit several times is that nature of industrial and economic revolutions is frequently unplanned, unpredictable by the intelligentsia and hence unanticipated. Except during the urgency of war, Governments are almost uniformly unable to drive technical or industrial change. Frequently their only role is to regulate and sometimes hinder development.

What can we learn from these three examples? Many things!

- None involved new developments in physics
- None involved major government sponsorship. Indeed some faced regulatory pushback (fracking); electric subsidies were put in place to encourage electric cars but for many years only Tesla benefited from them as other countries and companies took years to develop competing products.
- None of these game changers was predicted in 2000.
- After decades of incremental changes suddenly all three were rapidly implemented with major economic and cultural impacts.
- All were spearheaded by relatively small groups of people. One individual (Elon Musk) was responsible for two of the three.
- All were primarily privately funded.
- The US was the source and beneficiary of these three developments, helping ensure the US remained the worlds dominant economic power

Whole books can and should be written about these lessons. One intriguing one is if the US did not exist and Elon Musk could not immigrate here, would a Starlink network exist, would space launch costs have decreased, and would electric cars be ubiquitous? It should be noted that without SpaceX the US would likely have NO private launch providers. Furthermore the US would only have two old and relatively small auto manufacturers- GM and Ford.

What will the next twenty years bring. Many people see the tidal wave of change driven by AI as the next revolution. And they are probably right. However how this will change civilization is still uncertain and unpredictable. Some of these revolutionary capabilities will have application to space colonization, but exactly how is still unknown.

A large-scale civilization requires large-scale engineered infrastructure. The wealth experienced on earth and the ability to support over 8 billion people is due in large part to the efficiency of roads, railroads, pipelines, and power lines as well as tens of thousands of power plants, mines and factories. This infrastructure has been built over hundreds of years. In space none of this infrastructure currently exists.

This book will look at what it will take to build the large space infrastructure necessary for making humans multiplanetary. Multiplanetary implies that the colonies will be self-sustaining and therefore independent from earth. We will look at the technologies, the challenges, cost and scope of what will be required.

Building a space faring civilization will require tremendous infrastructure. The idea of colonizing space was first looked at seriously in the mid 1970's. Since then, while there have been incremental improvements made in various technologies there have been no radical improvements that will make it substantially easier. The conquest of space remains a formidable challenge. This book will explain how it can be done and what it will take.

Chapter 1 -The Conquest of Space

The challenges of living in space are considerably different and an order of magnitude larger than those encountered on earth. On large parts of the earth's surface people can exist with minimal or even no protection. We have evolved to function effectively in earth gravity and with a large layer of breathable air surrounding the surface providing protection against both small meteors as well as cosmic radiation. This relatively thick atmosphere, along with large oceans, serves as a large heat sink to minimize temperature extremes. Without this atmosphere and its greenhouse components, the earth would average -15C and the world would be frozen from pole to equator. The earth's rotation rate makes the nights and days of about 12 hours each, long enough to permit plants to grow but not too long as to cause day and night time temperatures to swing wildly. In short, we can live fairly comfortably on the earth with little or no artificial protection both due to its natural properties and the fact that we have evolved to live on it. Space on the other had is extremely hostile to life- the worst toxic dump on earth is benign compared to the hazards in space. Space will kill you in seconds without protection. One thing that needs to be understood about space is that life can exist only in an artificial environment- there will be no habitable "natural" environment in space. All human, plant or animal existence will be in manmade environments- including space stations, domed and underground cities, terraformed planets etc. Even terraformed planets will require maintenance and technological intervention to maintain their habitability. Survival in space will require constant conscious input… this will be no laisse faire existence.

Space is deadly everywhere, but most planets and moons have vastly different compositions and conditions that make unprotected life untenable in different ways. The following tables list some characteristics of the planets, major moons and planetoids:

Planet/ Moon/ Planetoid	Average Temp ©	Length of Day (Earth=1)	Atmo-Sphere Pressure (Earth=1)	Radiation environment (Surface)	Gravity (g)	Comments
Earth	18C	1	1	.274	1	
Mars	-60	1.026	.00628	27	.3794	
Titan	-180	15.945	1.45	Very Low at surface	.138	Thick atmosphere protects surface from Cosmic Radiation
Moon	-15	29.531	0	57	.1654	
Ganymede	-163	7.154	0		.146	Largest moon in Solar System
Callisto	-134	16.689	0		.126	
Ceres	-110	.378	0		.029	Largest Asteroid
Triton	-235	5.877	.00014		.0794	
Mercury	-173 to 427	176	0		.38	
Venus	464	116.75	92	Very Low at Surface	.904	Thick atmosphere protects surface from Cosmic Radiation
Eris	-237	15.786	Trace		.084	Largest Kuiper Belt object found to date

Table 1-1 Properties of some prominent Solar System planetoids.

This table gives a list of the MOST earthlike bodies in the Solar System. I have not listed the millions of small asteroids or comets, or the moons Europa or Io (where radiation levels are extreme due to the proximity of Jupiter's magnetic field), or any of the giant gaseous planets like Jupiter, Saturn, Uranus or Neptune which have no solid surface.

What this table tells us is that if we want an earthlike planet, we will not find it. In all cases the surface gravity of these objects is far less than that of the earth. In many cases these bodies have no atmosphere. In the couple of exceptions (Titan and Venus), they do have substantial atmospheres (more massive than the earths) but their temperatures are not conducive to life- far below zero on Titan, and far above the boiling point for Venus. For these reasons many space futurists believe that wholly artificial space stations with earth like e conditions will be the best place to house humans. Nevertheless, planets, moons, asteroids and comets will remain important in any colonization efforts as they would provide all the required construction materials.

Besides the physical characteristics of space and the various bodies spread throughout, space is also vast- both in physical dimensions as well as material and energy resources available. To live and thrive in space will require us to tap into these resources. In many cases, tremendous power is required to access and exploit raw materials, and to keep colonists alive. Where will we get these resources and how will be obtain and control the power associated with it?

The vast distances required to travel to the various bodies in the solar system provide additional challenges for the people, equipment and raw materials. In this book I will look at various technologies to address these challenges, including rockets of various types, as well as more unique and challenging designs such as Cyclers, Solar Sails, Space Elevators, Momentum Transfer Devices and Mass Drivers.

We will begin our analysis by looking at what it takes to build artificial environments to permit us to survive in space and then look at where we will get the materials to construct these environments. Currently almost everything needed to live in space has to be brought from earth at tremendous costs in energy and materials. This severely limits the size of any space structure as well as the number of people that can be supported. After nearly 70 years of space exploration, we average little more than half a dozen people in space at any one time. This small presence is driven both by the engineering challenges of going into space, but even more importantly the fact that all materials used for survival have to be brought up from earth at high costs- it simply costs too much to build and support a large space presence.

Over the next few decades, it is hoped that some modest industries are created to begin sourcing raw materials from space. However, this growth in space industrial capabilities will be slow and for the near future (within this century), colonization of space will likely be limited to space stations, both large and small, as well as domed or underground colonies on the moon and Mars. As the space infrastructure grows, colonies can be expanded to more distant bodies and may include terraformed planets and generational starships. Until then, both space stations and underground colonies are likely limited to a couple of million inhabitants and even that will require a transportation and mining infrastructure comparable to what has been built on earth.

How will the Conquest of Space Occur?

In this book we will look at the next several centuries of colonization- what it will take and how it will evolve. Towards the end of this time, we may find it desirable to terraform a planet or moon, or perhaps even build one from scratch. The terraforming of a moon or construction of an artificial planet are technically feasible challenges but require vast resources and, in some cases, thousands of years. Nevertheless, assuming human technological and engineering advances continue, and a large and robust space industry is developed over the next few hundred years, it may be possible in the 22 or 23rd century to begin terraforming a planet or moon. However, make no bones about it, the nature of space, its vastness, its resources and its dangers will require it to be a conquest in every sense of the word- space will not surrender easily.

As on Earth, large human populations require:

- Raw Materials. Where will they come from and how will we mine them?
- Transportation of both People and Resources. Each transportation mode will require different solutions- people will require fast, safe and comfortable travel. Cargo and Raw materials will require large quantities (mass) but at much slower speeds.
- Power. The amount of power needed for transportation, colonies, mining etc. are tremendous. Where will this power come from?

After we look at the raw materials, power and transportation challenges, we will look at building large space stations, including how they would be built and what they will look like. We will look further down the road at large colonies on various planets and moons and then look even further and examine the feasibility and challenges of terraforming various bodies in the solar system including the most challenging goal of building a planet from scratch and using resources from the Asteroid Belt, other planets, the Kuiper belt and Oort cloud.

Magnitude of Conquest

What will it take to effectively conquer space? In short, advanced technology, large infrastructure, and vast resource exploitation- and most importantly, dedicated and driven people.

As we go through this book, we will identify the resources needed for space colonization. For large scale projects like terraforming, in particular the creation of planetary atmospheres, the resource requirements will be literally astronomical. Nevertheless, the resources for even a large space station, and substantial colonies on the moon and Mars are within the realm of current industrial and technological capabilities.

A Short History

Ever since humans began speculating on the possibility of reaching orbit and journeying to other astronomical bodies like the moon and planets, people have wondered what we would find there. In the late 19th and early 20th centuries, many wondered as to whether there was intelligent life on some of these planets and even more alarmingly, whether it would be hostile. Most of this fiction, including tales from Jules Verne and H. G. Wells were based on a very limited knowledge of the actual conditions of space and limited understanding of engineering required but instead counted on that most abundant of human skills- imagination, to fill in the gaps. Usually these stories were exceptionally entertaining, but extremely unrealistic. As the twentieth century advanced, stories continued to get more speculative and spectacular, to include travel to distant planets in the Solar System and then to the stars.

Even though these stories were entertaining, they frequently bypassed the difficult engineering challenges in favor of narrative, adventure or morality.

Over the last hundred years our knowledge of both the conditions in outer space to include the planets and moons, as well as our engineering capabilities, has grown tremendously. Unfortunately, our physics and materials sciences have not advanced to the state of the more speculative science fiction stories in which many engineering marvels exist including faster than light travel, true artificial gravity (not centripetal), powerful but compact magical power supplies, or even more prosaic capabilities like long term suspended animation. None of these technologies have gotten much closer than they were 60 years ago. Since the explosion of practical and theorhetical knowledge that occurred during WW II and the immediate aftermath, little revolutionary engineering has occurred since then. Fission power was first seriously investigated during WW2 and the first practical commercial and military power plants were created in the 1950's and 60's and little improvement has been made since then. Commercial Nuclear Power Plants, as well as those used on Naval ships and submarines, are certainly incrementally safer, more compact and more efficient, but their basic designs are the same as those built sixty years ago. After the discovery of fission and fusion, there have been no new sources of power uncovered for nearly a century and many physicists doubt there ever will be. Fission and Fusion, as well as gravitational and kinetic energy appear to account for all the observed power in our universe.

As with Nuclear power, rockets have had few major technological breakthroughs over the last few decades. Large rockets were first built during WW II and the basic technology has not changed much. Until SpaceX many rockets in use were derivatives of the designs from the 1950's. While their efficiency, reliability and capabilities have incrementally improved with better materials and computer aided designs, a rocket scientist from the 1950's would easily recognize a rocket built today.

A similar story can be found in materials science. Certainly composites and other artificial materials have capabilities that may exceed traditional materials in certain applications, but even these frequently come with offsetting negatives. There are no new metals that can be discovered, and at best, we can assume continued tweaks in alloys for certain applications. Except for the distant and perhaps impossible materials made of carbon nanotubes and such (more on this in Chapter ##) the materials we have today are the materials we will have the rest of this century and the next.

After carbon nanotube material improvements, there is one additional technology that could drastically change the way space is conquered- fusion power. Fusion promises revolutionary improvements in power and propulsion capabilities which we will explore in this book. However, except in the explosion of an H-Bomb, practical fusion which would provide compact, efficient and high power remains out of our grasp after over 70 years of effort. Even though there has been incremental improvement over the decades, practical fusion likely requires another 50 years of concerted effort- and lightweight reactors perhaps another fifty, even if they prove possible.

What these facts suggest is that most technological improvements over the next century or two will likely be incremental and not revolutionary. There is no new physics out there. The good news is that we have had, since the 1970's, the technological capability to visit the nearer planets and to build large space stations. Unfortunately, the lack of breakthroughs in physics, along with the modest improvement in industrial and technological capabilities means that even though we can "conquer" space, the costs and challenges remain stratospheric.

The first serious attempts at identifying and conducting preliminary design for the large-scale development of space were done in 1975 and popularized in several books including the High Frontier by Gerard K O'Neill. In the 1970's space was primarily looked at a place of virtually unlimited resources and perhaps even a safety valve for an excessive population growth. Energy, in the form of sunlight, was essentially infinite and free, the construction of colonies was conceived as a means of reducing human population pressures, and its vast mineral resources were a means of getting around Malthusian limits to growth. While some of these ideas retain some validity, many of them have been proven flawed.

Since the mid-1970's fundamental technological progress has been slow and halting, but nevertheless real. Even more impressive has been the continued incremental industrial and economic growth around the world. The widespread famines, exhaustion of resources, tremendous pollution and shortened lifespans that were predicted have all failed to occur- proving that predicting the future is both problematic and frequently driven by cultural narratives rather than intellectual rigor. Most of the intelligentsia of the 1970's forecast a much poorer world by the 2020's and instead the opposites occurred. To compare the world of 1975 with the world of today:

	1975	2025	2075	
Population	4.07billion	8.2billion	10billion	
Worldwide GDP	32 Trillion	135 Trillion		
Energy Usage	76,871	183,230		
Average Per Capita Income	$9700 (1990)	$17527 (2022)		
Oil Reserves	93 billion t (1980)	236 billion t (2020)		
World Steel Production	643 million mt	1883 million mt (2023)		
World Mining		1837 billion mt (Reichl, 2024, p. 4); about 16billion mt is coal		
Concrete Production	1.46 billion cubic meters	14 billion cubic meters		
Annual Rocket Launches	132 in 1975 and 1976	261 (2024)		Record flight activity of 1975/76 would not be matched until 2021
Cost to Orbit	≈$10,000 kg	≈$2,000 kg		Not inflation adjusted!
Rocket Engines	Chemical	Chemical, Ion		
Material Science	Aluminum, Steel	Aluminum, Steel, Composites, Stainless Steel		
Solar Panels	Efficiency 16%;	About 30%; costs have decreased over 90%		
Computer Science	Primitive	Extremely Capable	Advanced AI	
Space Nuclear Power	RTGs	RTGs	Fission	
Food Production (Cereal)	1.36 bilion tons	3.06 billion tons		

Table 1-2 Selected World Statistics 1978, 2025, 2075

What this tells us is that the world has gotten economically much richer over the last fifty years. While the population has increased by 200%, food production has increased by 225%, energy usage by 240% and GDP by 413%. Contrary to the intellectually appealing ideas promulgated in books such as "Limits to Growth" none of their predictions of impending resource exhaustion ever came to pass. In the 1970's the idea of peak oil in which oil production was to begin a long and irreversible decline as reserves dwindled was a widely accepted and some would say self-evident theory. As Table 2 shows us, despite ever increasing oil production, the amount of reserves has in fact increased 254% over the last forty years.

In contrast to the predictions of many intellectuals in the 1970's as the world has gotten more populated, people have gotten progressively richer since economic growth has been faster than population growth. Most of this economic growth has been in poorer countries which in general have seen a greater relative improvement than that experienced by the more developed countries, especially in those poor countries that have liberalized and decentralized their economies.

One hypothesis explaining this diversion between intellectual thought and reality is that educated people frequently are susceptible to group think and social narratives and their predictions are just as flawed, and sometimes less accurate, than a random person in the streets. Instead, their education levels make them feel more comfortable in their pronouncements, even if their statements and predictions are no more accurate. In many ways this is ominous, as the general perception is that an educated population will make better decisions and will help steer a society by making better decisions. The reality is that narrative and social pressure frequently are more important than intellectual rigor. Intellectuals frequently underestimate the motivating power individuals and markets to make creative solutions that increase wealth faster than centralized planners ever could.

We can postulate several other theories from this table and our statements on technology:

    - Progress is incremental rather than revolutionary. There are no radical new technologies or physics invented, but only a continuous refinement (sometimes substantial) of engineering and physics principles. Time travel, warping of space, newly discovered energy sources, none of these have occurred over the last fifty years. The Green Revolution was systemic and emphasized Genetically Modified Organisms, (sometimes referred to as Frankenfoods by wealthy intellectuals). Nevertheless, modern genetically modified organisms, along with improved agricultural techniques and improved weather forecasts have led to steady but substantive improvements in crop output- so much so that food production has grown faster than population growth.
- Any drastic improvement in a technology will likely be brought about by revolutions that are not predictable. Some examples:
    - Fracking was developed be private industry with little encouragement by the government- indeed the government has actively sought to subsidize OTHER energy options at the expense of oil and gas. Despite this fracking has had a considerably greater impact to worldwide energy production than any government sponsored programs (biodiesel, Solar, Wind) and has kept oil and gas relatively cheap, improving the lives of poor people and around the world, as well as undercutting the clout of many communist and totalitarian states including Venezuela and Russia.

- The tremendous improvement in electronics and computer performance including solid state memory was incremental but continuous, and eventually led to applications and hardware capabilities that could not be imagined fifty years ago. No one foresaw that small hand held phones could also act as a camera or video recorder, act as a music (and video) players with thousands of songs, monitor your health, act as digital payment device, and provide you or your car with global positioning to within a couple of meters.

In general, technological improvements and their applications are unpredictable while economic improvement are gradual and cumulative. Artificial Intelligence is one future technology whose impact on economic performance is impossible to predict. It may be revolutionary, or like nuclear fission over the last fifty years, subject us to only gradual improvement.

The lack of radical technological developments, but even more importantly, the lack of progress in large national and international programs (NASA, Ariane), Fusion Power with the International Thermonuclear Experimental Reactor (ITER), widespread implementation of green energy (including solar, wind and advanced fission reactors) also points to the general ineffectiveness of government projects. If the government(s) takes the lead on development, progress is extremely slow- unless given urgency because of war or national competition. Based on this lack of progress, ideas of a robust space program directed by centralized government planning as part of a national industrial policy, appear naive. Governments instead serve a useful function by doing basic research and perhaps some seed money or incentives to private organizations who make the real progress.

Most people are agnostic over who should take the lead- whether government or private entities, in space. If they have any interest in space initiatives, they just want it done. Sometimes political appointments and people put in charge of space development are more interested in narratives or politics rather than the pragmatic concerns of people who actually want to get things done. If governments can drive a robust colonizing program, then few would be upset. However, the key is progress- governments worldwide have taken the lead for over 60 years and literally no major physical progress has been made. It becomes pretty obvious that governments are structurally and institutionally unable to take the lead in the actual colonization of the solar system.

Even though governments will play little role in the colonization of space they can stop it. For those who are interested in space colonization, the most we can hope for from the government is support with the funding of technology and basic research and development, while keeping a streamlined regulatory environment that permits private corporations and individuals to actually conquer space. In Chapter 20 we will discuss how space progress can be stopped or inhibited via government and/or society.

Summary and Conclusions

Most of the technology required for the conquest of space is already in existence and has been for the last fifty years. Radical new technologies like antigravity, stargates, Faster Than Light (FTL) travel, artificial gravity (not centripetally generated), long term suspended animation, new extremely powerful but compact power supplies, superstrong carbon tape, and radically genetically engineered humans are not likely to occur for many centuries if ever.

Improvements are occurring gradually. Since the first serious looks at various colonization schemes in the 1970’s some real incremental technological progress has occurred including:

- Computers are vastly more capable which permits more accurate designs of rockets and equipment, as well as automating of many tasks
- Rockets are incrementally more efficient and use an expanded inventory of different propellants
- Ion and Electrostatic Engines are developed and in use for low thrust but long duration missions
- Laser technology has improved substantially to be more efficient, compact and powerful. They can be used for communication as well as active defense against micrometeoroids
- Material science has continued to slowly improve. Additional metal alloys have been developed for specific applications. Composite capabilities have shown some improvement
- Over the last decade or so the cost for carrying payloads into space has decreased by up to 90% with potential to reduce costs even more.

As Table 2 pointed out our ability to colonize space has been improving because of miscellaneous but countless incremental improvements in technology, and improved economics including a substantial growth in the earth industrial capabilities. Space may not have become vastly easier to colonize, but the world economy is far larger than it was fifty years ago and improved incremental technological improvements make it a proportionally smaller effort.

In later chapters we will look at some future technologies that may be developed over the next century or so that will further enhance mankind's ability to conquer space. Broadly they are:

- High power, low mass fission reactors
- Fusion reactors for both power and propulsion
- Higher strength but lightweight carbon materials- not as strong as their theorhetical limits but much stronger and able to be made in larger quantities than currently available. These would be most useful for Solar Sails and perhaps for smaller, non-earth base Space Elevators.

Chapter 2 -Scale of the Solar System

Resources- where are they located and how much is available?

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 we shall see in Chapter 3, for every kg of cargo placed in orbit or sent into deep space, ten or twenty times more fuel is used to get it into space. For larger missions, spacecraft, or 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 2-1).

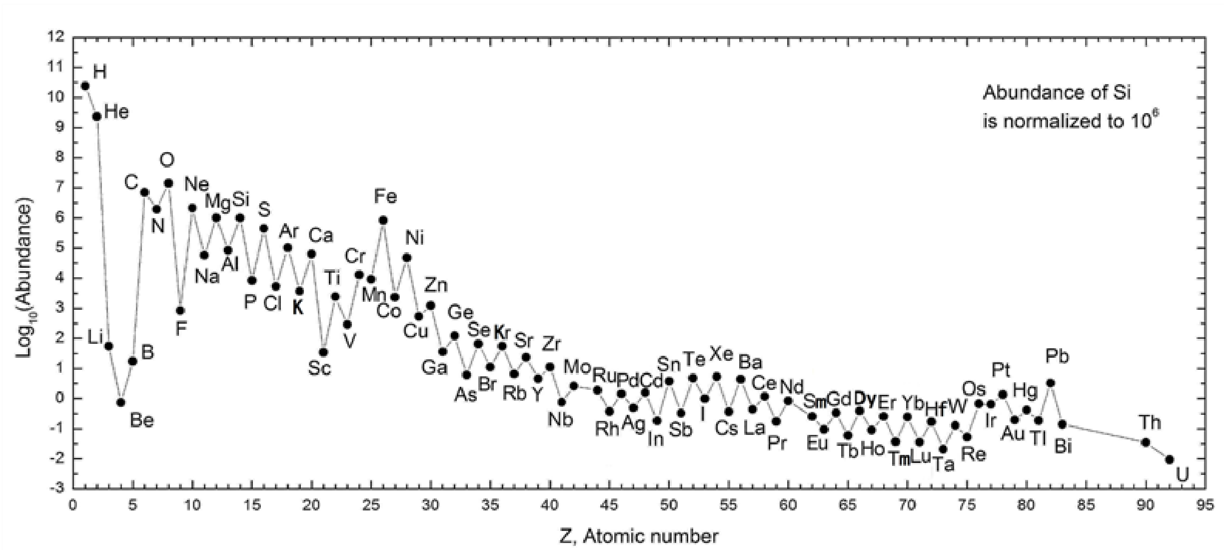


Figure 2-1 Solar Nebula Abundance Plotted Atomic Number VS Abundance Log Scale (Lodders, Solar System Abundances, 2007)

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, hydrogen is the most common element… 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 suns 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 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.

CHAPTER 2. MATTER AND ITS ATOMIC STRUCTURE

Table 2.2: Most abundant chemical elements in the solar nebula

Atomic number Z	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 2-2 (Grevesse & Sauval, CRC Handbook of Chemistry and Physics Rev 85, 161, 1986-1987)

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 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.

The 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.

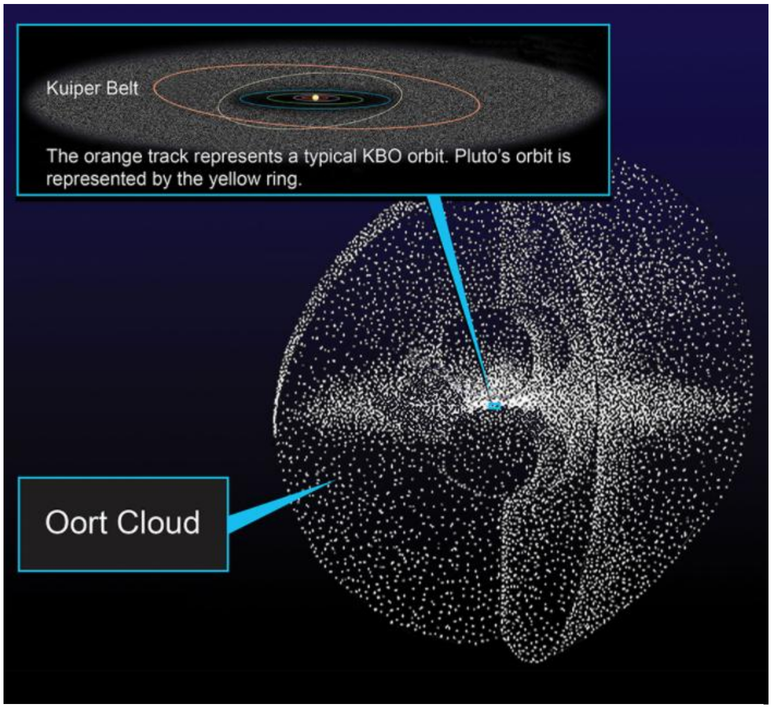


Figure 2-2 The Solar System- Kuiper Belt and Oort Cloud (Yeoman, n.d.)

There have been many studies, and space probes that have tried to identify the resources that are available on the 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.

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 2-3).

Lunar surface chemical composition[1]

Compound	Formula	Composition	
		Maria	Highlands
silica	SiO_2	45.4%	45.5%
alumina	Al_2O_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_2O	0.6%	0.6%
		99.9%	**100.0%**

Table 2-3 Lunar Surface Chemical Composition (Taylor S. R., 1975)

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 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.

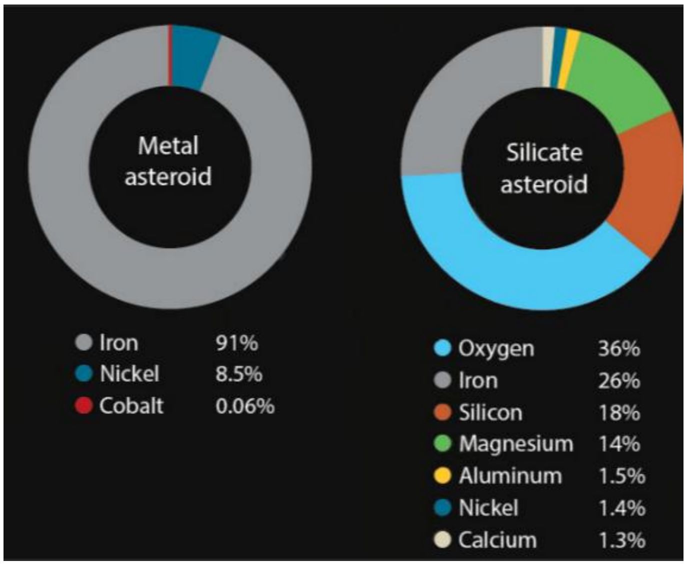


Figure 2-3 M-Type and S-Type Composition (Courtesy NASA)

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.

With space, resources are virtually inexhaustible. Unfortunately, these resources are currently impossible to access. This is due to the distances involved, the lack of a pace industry or infrastructure, and in some cases the physical difficulties of accessing. In 75years of space exploration, the only space resource that has been tapped is the suns radiation used to power spacecraft. The Apollo missions brought back over 400kg of lunar soil for study, but other than a few robotic missions to the moon, and a couple of asteroids which have returned a few more kg, no material has been collected and brought back to earth.

Jupiter, Saturn, Uranus and Neptune are truly massive planets that are collectively almost five hundred times more massive than the entire earth. The fact that they lack a traditional surface, and have very deep gravity wells make getting their resources very difficult, means, with the possible exception of Uranus, at least within the next few centuries humans will not visit or colonize these worlds. The main accessible resource they provide are various volatiles, primarily hydrogen, helium, and various other gases. Using their deep atmospheres to brake any approach is possible (and to some limited extents it has been done with the Galileo probe) and makes getting to their moons much easier (though the radiation belts that a spacecraft would have to pass through are still problematic) but we do not have the rocket technology available that provides both the high thrust and specific impulse available to descend deep into these planets' atmospheres, grab their resources, and then accelerate back into orbit.

Even eliminating these giant planets, there remain vast resources that are far easier to access. Essentially the material wealth of all materials in the solar system is infinite. Partly this is because most materials can be recycled, and matter, except in extreme instances like a nuclear reaction, does not get destroyed but is endlessly available for reuse. In addition, the material that is available to be mined from the various moons and small planets is many billions of times more than what humans have used to date.

Below are a summary of the various bodies in the solar system with their approximate mass:

	Typical Characteristics	Cumulative Numbers and Mass	Comments
Mass of Earth		5.972×10^{24}	
Large Planets	Mostly volatiles or water	2.656×10^{27}	Jupiter, Saturn, Uranus, Neptune; most resources are unreachable
Small Planets (including Earth)	High in metals; most have some water, volatiles	1.1811×10^{25}	Mercury, Venus, Earth, Mars
Moons	Varies. Some are high in metals, others high in volatiles, water	631.1×10^{21}	Moon, Io, Europa, Callisto, Ganymede, Titan, Triton
Asteroids	High in metals, some have water, carbon	2.23×10^{21}	Ceres, Vesta, Pallas, Psyche make up an estimated 60% of the mass of the asteroids. Ceres alone makes up 40% of the mass
Kuiper Belt Objects to Include Scattered Disc and Comets	High in water, volatiles, some metals	6×10^{23}	Includes Minor Planets in Scattered Disc- Pluto, Eris, Sedna
Oort Cloud	High in water, Volatiles	6.6×10^{25}	Speculated but believed to consist of trillions of bodies over 1km

Table 2-4

It is likely that large mining operations will be built on some of the larger bodies in the Solar System. Certain bulk materials will account for a vast majority of the mass moved around the solar system- the first six materials in Table 2-5 will probably account for above 95% of the materials sourced and transported.

Materials by approximate order of mass	Uses	Sources
Undifferentiated Regolith, Soil	Shielding for spacecraft, soil for crops	Moon, C-type asteroids
Water	Ice for shielding, Water, Source for Oxygen/Hydrogen engines	Mars, Ceres and C-type asteroids, Ganymede, Callisto
Iron	Steel manufacturing for ships and colonies	Moon, Vesta, Psyche and other M-type asteroids
Titanium	Ships and colony construction	Moon
Aluminum	Ships and colony construction	Moon, Vesta, Psyche and other M-type asteroids
Nitrogen and Ammonia	For ships and colony atmospheres	Titan, Venus, Pluto, C-type asteroids, Kuiper Belt
Misc Metals (Copper, Nickel, Chromium, Cobalt)	Ships and colony construction	Earth, Moon, Vesta, Psyche and other M-type asteroids
Carbon	Required for life	Earth, C-type asteroids, Ganymede, Callisto
Phosphorus, Chlorine, Potassium, Sodium	Required for life	C-type asteroids, Ganymede, Callisto
Uranium and Thorium		Earth; Moon; Mars; possibly Asteroids; M- type Asteroid
Helium 3	Fusion power plants	Moon, Asteroids

Table 2-5

The mining of these materials will require large, permanently manned colonies. Candidate locations for these colonies and mines are:

Body	Most common export	Comments
Moon	Regolith, Aluminum, Iron, Titanium	Low Gravity. Metals will be used for cities and large domes.
Mars	Aluminum, Iron, Titanium, Water, Carbon	Low Gravity. Consider for terraforming
Titan	Nitrogen, Water	Low Gravity. Prime Candidate
Ganymede	Water	Low Gravity.
Callisto	Water	Low Gravity.
Triton	Water	Large Space Station or Ring City
Ceres	Aluminum, Iron, Titanium, Water	Large Space Station or Ring City
Vesta	Aluminum, Iron, Titanium, Nickel	Large Space Station or Ring City
Eris	Water, ?	Large Space Station or Ring City
Pluto	Nitrogen	Large Space Station or Ring City

Table 2-6 Primary Targets

Several other worlds would be extremely challenging to colonize and exploit and can be considered as "long term projects" (after 23rd century).

Body	Characteristics	Comments
Mercury	High Temperature High subatomic cosmic radiation Deep in Suns gravity well making it difficult to reach	High radiation and temperature. Temperature would need to be mitigated via Solar Occulus (Shade). Slow rotation rate will also require large solar mirror to provide a more normal day/night cycle. Underground or buried structures would shield against radiation. Difficult to reach Mercury as it is

		deep within the Sun's gravity well and ships and their crew/cargo will be subject to high temperatures and solar originated cosmic radiation.
Venus	High Temperature High subatomic cosmic radiation Deep in Suns gravity well making it difficult to reach	High radiation and temperature. Temperature would need to be mitigated via Solar Occulus. Extensive atmospheric modifications to eliminate CO2; Slow rotation rate will require large solar mirror to provide a more normal day/night cycle.
Uranus		Atmospheric floating cities; deep gravity well but less than other of the giant planets

Table 2-7 Secondary Targets- more challenging because of severity of environments

We mentioned that the gas giants, in general would not be suitable or even possible to colonize. However, with additional technological development, combined with perhaps genetic modifications of humans, the gas giants, as well as the moon Io and Europa may become habitable in the distant future.

An appreciation 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 usually originate in the Oort cloud are usually only a little denser than water (Specific Gravity (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 2.5.

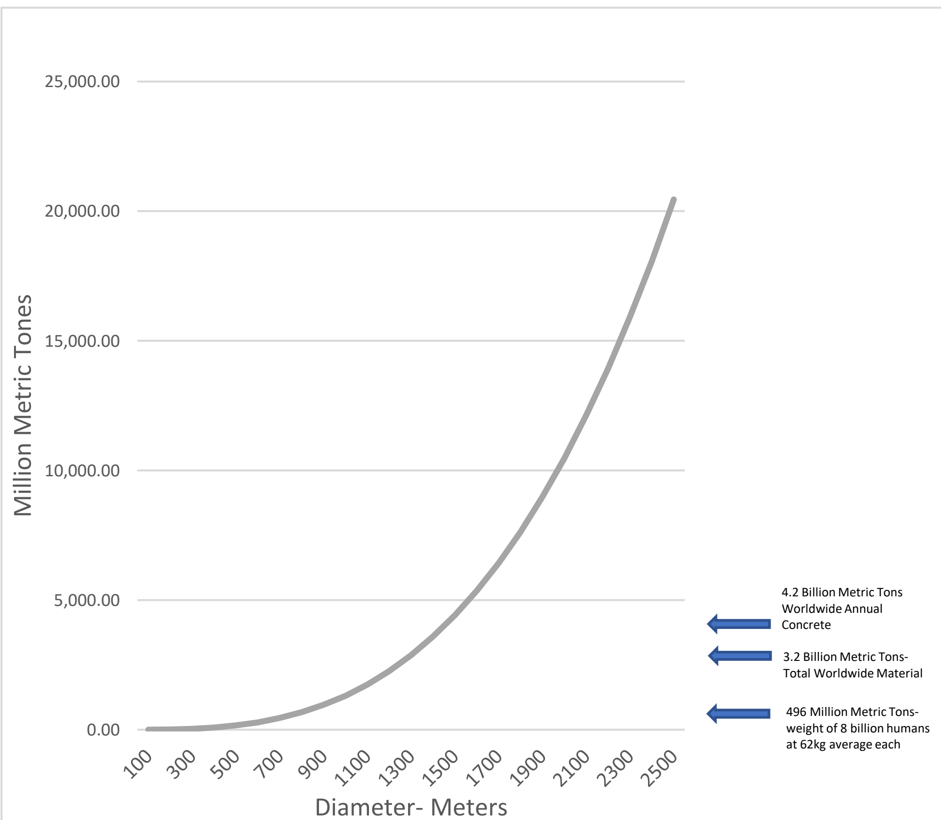


Figure 2-5 Diameter of Asteroid vs Mass (assuming 2.5SG) In Human Terms (Bhutada, 2021)

What this chart shows is that even small asteroids only a kilometer or two in diameter has a tremendous mass. 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 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.

To give some perspective, humans have cumulatively extracted about 1.4 trillion barrels of oil from the ground (Institute for Environmental Research and Education (IERE), 2025)- or about 224 cubic kilometers of oil or 189 billion metric tons- or 1.89 $x10^{14}$ kg. The mass of water in Lake Superior is about 1.21x 10^{16} kg so all the oil pumped out of the earth since the beginning of the industrial revolution is equal to about 1/64th of the mass of the water in Lake Superior.

The asteroids are an abundant source of various key elements, but every asteroid has its own unique history and therefore, composition. Later we will look at nuclear power and where elements like Uranium and Thorium can be sourced. For instance, thorium is most likely found in S-type (silicate rich) asteroids like Juno, Eunomia, and Amphitrite. Somewhat less enrichment but some thorium would be in the the silicate but also carbon rich asteroids like Ceres, Pallas and Hagiea. A metal rich asteroid like Psyche is likely to have virtually zero thorium.

Size

As with the available resources, the size of the Solar System is so vast that it is hard to describe adequately. Throughout this book, its size will be emphasized as it is one of the factors that make colonizing so difficult. In many cases, an energy efficient transfer orbit will take years or decades to reach their goal. Table 2-8 shows the distance planets are from the sun- in the case of Neptune, it orbits 30 AU from the sun. An AU is a unit of measure equal to the distance from the Sun to the Earth- about 150,000,000 kilometers. Neptune is just over 30x further than the Earths distance to the sun. The moon, the only astronomical body that has been visited be humans is a little less than 1/400th of an AU.

Inventory of Planets

The following table shows some of the key characteristics of the 23 largest bodies in the solar system sorted by mass. They range from the largest planet, Jupiter (about 318 times the mass of the Earth), to Ceres, the smallest item on the list:

Name	Type (Planet, Moon, Planetoid)	Mass (10^{21}kg)	Distance from Sun (AU)	Length of Day (Synodic)	Average Temp (K)	Gravity (Earth=1)	Comments
Jupiter	Planet	1898187	5.2038	9.9258h	88	2.528	No surface; high gravity
Saturn	Planet	568317	9.5826	10.5433h		1.065	No surface; high gravity
Neptune	Planet	102413	30.07	16.11h	72	1.137	No surface; high gravity
Uranus	Planet	86813	19.19	17.2336h	76	.866	
Earth	Planet	5972.4	1	24h	252	1	
Venus	Planet	4867.5		116.7d		.91	High Surface Temperature and pressure
Mars	Planet	647.71		24.7h		.38	
Mercury	Planet	330.11	115.	176d		.38	High Radiation and Temperature
Ganymede	Moon	148.2	5.2038	7.15d		.146	
Titan	Moon	134.5	9.5826	15.95d		.138	
Callisto	Moon	107.6	5.2038	16.69d		.126	
Io	Moon	89.32	5.2038	1.77d		.183	High Radiation
Moon	Moon	73.46	1	29.53d		.165	
Europa	Moon	48	5.2038	3.55d		.134	High Radiation

Triton	Moon	21.39	30.07	5.88d		.079	
Eris	Planetoid	16.6	68.051	25.9h	42	.082	Extreme Distance
Pluto	Planetoid	13.03	39.482	6.387d	44	.0632	Extreme Distance
Haumea	Planetoid	4.01	43.116	3.92h		.044	Extreme Distance
Titania	Moon	3.4	19.19	8.71d		.0378	
Makemake	Planetoid	3.1		7.77h		.05	Extreme Distance
Oberon	Moon	3.08	19.19	13.46d		.035	
Rhea	Moon	2.307	9.5826	4.52d		.026	
Iapetus	Moon	1.806	9.5826	79.3d		.023	
Gongong	Planetoid	1.75	67.485	22.4h		.0183	Extreme Distance
Charon	Planetoid	1.56	39.482	6.39d		.029	Extreme Distance
Umbriel	Moon	1.28	19.19	4.14d		.0257	
Aeriel	Moon	1.25	19.19	2.52d		.0251	
Quaoar	Planetoid	1.20				.02	
Dione	Moon	1.095		2.74d		.023	
Ceres	Planetoid	.938	2.77	9.07h	173	.029	Largest of the asteroids

Table 2-8; Green highlight in Comments section means Early Colonizing (0-100 years); Blue means Mid-term colonizing (100-200 years; Yellow means late colonizing (200+ years); Red means unlikely to ever be colonized.

Except for the items in Red, many of these objects will likely have some sort of human presence on them in the coming centuries- though on many, human occupation may be transient. In the above it is clear- the gas giants have most of the Solar Systems mass outside of the sun, and that the rocky planets have substantially less mass and cluster together in size, with another large drop down to the remaining moons and planetoids. Ceres, the largest asteroid, is relatively small compared to the planets and larger moons.

Several of these planets (the gas giants) have no traditional surface so large colonies will not be established. However, it is possible to build floating cities in their atmospheres. Uranus in particular has a reasonable gravity making access a bit easier than the others. With that being said, these planets do not have much in the way of useful resources, with the exception of helium. Helium3 is a minor component of Helium but has significant potential for power generation (we will cover its importance to Fusion in chapter 3), but the collection of this material will likely be automated. Nevertheless, it is possible to build floating cities on these gas giants and we will discuss the practicality of this in Chapter 10. Jupiter is likely never to have a floating city built due to its very strong and deep gravity well, but Uranus, Neptune and Saturn may be possible (though progressively more challenging).

Several other bodies will likely never have permanent human presence- specifically Io and Europa. Since they orbit the planet Jupiter, they are both deep in the planets gravity well making them difficult to reach. Even more important is that both are subject to extreme radiation levels from Jupiter's geo-magnetic field that would be difficult to shield against. Even if you bury a colony deep below the surface, your spacecraft that would approach the moon would be fried with a large amount of radiation. Furthermore, IO is extremely volcanic and subject to massive surface faulting, volcano's and lava. If some sort of life were found beneath the ice crust of Europa, it is possible that scientist may visit it's the moon for short periods of time- but they will have to quickly get under the surface ice to prevent radiation poisoning. Others, like Venus and perhaps even Mercury, may be inhabited but both will need large terraforming projects (see Chapter 15).

Energy

The most important resource is the one that cannot be recycled- energy. With enough energy, most resources can be accessed. Energy in the universe boils down to two primary sources… Nuclear (primarily fusion), and Kinetic Energy (primarily the orbital or rotational energy of large bodies). Both are likely to be used in the future.

Fusion occurs far below the surface of a star where the high pressure, density and temperatures ensure that occasionally items like hydrogen will fuse together and create energy. Fusion can only occur deep within the star where those conditions exist.

Another source of nuclear power is fission. Fission creates heat/energy and as such can be a source of power. Fission is responsible for most of the elevated temperature at the Earths core. However, in general fission products are not a major source of energy in the Universe. The earth has some Uranium and Thorium in its crust that can be used for fission reactors. Whether directly or indirectly fissionable resources ultimately came from a combination of fusion and kinetic energy.

Within stars, fusion leads to heavier materials. Small stars primarily create helium, but larger stars can create heavier elements up to Iron. Fusion of heavier and heavier elements can occur because each of these reactions create more energy than was needed to smash atoms together but as the elements get closer to iron, this net energy gain is less until we hit iron where less energy is released during fusion than the energy required to fuse the atoms. At this stage fusion would normally stop, but when iron is created the energy released is to small to maintain the star and it starts to collapse. The tremendous kinetic energy from the ten's of thousands of miles of the star that is no longer held up by the radiation pressure is added to the stars core. Depending on the size of the star, several things can happen- the star can essentially rebound and totally explode or may only partially explode. For a truly massive star the star may just continue to collapse into a black hole. However, for the less exteme cases where the star explodes the tremendous amount of kinetic energy of the initial collapse can create heavier elements than iron.

Uranium and Thorium resources are available on the rocky planets and asteroids, but their concentrations are fairly low. Uranium and to a lesser extent Thorium are relatively rare in the solar system in general. During the initial exploration and colonization of the Solar System, Fission reactors will likely be the primary, and in many cases the only, source of power- especially for ships and colonies operating outside of the orbit of Mars.

Though relatively rare, the large quantity of raw material in the Solar System means that Uranium supplies are essentially inexhaustible but the rareness means that to obtain even small amounts of Uranium tens of thousands of tons of material may need to be processed. Uranium, because of it is a lithophile (rock loving) element, combining with oxygen and silicate, can be found in higher economic quantities than would be expected- the geology of the earth withs long term periods of partial melting and plate tectonics allowed Uranium to be enriched. Some estimates have it that easily available Uranium sources may be exhausted within 700 years. Currently Uranium is disposed of when reactor fuel is replaced, but reprocessing can be done which would reduce the amount of new Uranium that would need to be refined as well as reducing the amount of nuclear waste. Reprocessing of spent nuclear fuel as well as accessing currently inaccessible fissionable materials dissolved in the sea, may extended the Uranium supply for hundreds of millions of years.

The Moon, Mars and other similar bodies did not experience the same active process which means Uranium is more evenly scattered throughout the crust in very low concentrations. Substantial sources of Uranium still exist in these and other bodies, their recoverability is much more difficult since they are very low concentrations (on the order of the solar nebula of .2ppm or less). Thorium is also at low concentrations and scattered throughout the solar system, but in general is 3-4x more prevalent than Uranium meaning that it will likely become a major resource for future nuclear power (see Chapter 6).

The biggest source of energy in our solar system comes from the sun, which converts 60000 tons of hydrogen into 56,000 tons of helium and 4000 tons of energy every second. Solar energy is the only space resource currently used by spacecraft- all other resources are brought from earth. Solar power of one sort or other will likely be the primary source of power for earth orbiting and L5 colonies, and any colonies inside the earth orbit (ie Mercury). Mars is likely to use both solar and nuclear power. For Jupiter and beyond ships and colonies will use nuclear power.

Another concept that we will look at in Chapter 7 and 12 is beaming of power. In beamed power, energy is created at one location (either by a nuclear reactor or a solar power plant) and beamed to where it is needed. This has potential for things like bringing down solar power to earth via microwaves or providing power or thrust to deep space vehicles.

Currently most of the prodigious quantity of energy released by the sun is wasted… based on the diameter of the earth and the surface area of a sphere at the earths distance from the sun, the earth intercepts only .0000004% of the suns radiation … nature is truly inefficient. All this solar energy is just waiting to be tapped.

It is obvious that the amount of Energy for a particular area decreases as we get further from the sun. This means that solar panels will collect less energy and the temperature of the spaceship, planet, asteroid or whatever body will drop off with distance. Figure 2-6 shows the average Watts per m^2 and the expected surface temperature of various planets, ignoring possible greenhouse gas contributions.

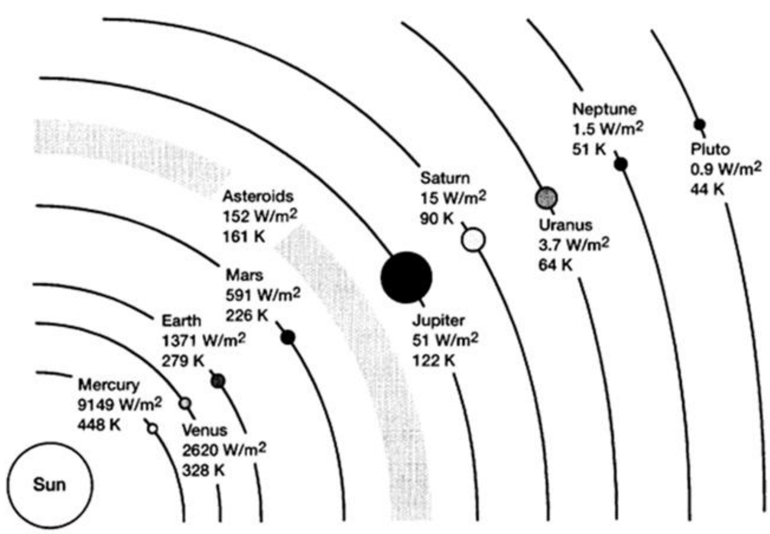


Figure 2.—Solar heat flux and spacecraft surface temperatures at various planetary orbit distances.

Figure 2-6 Solar Heat Flux at Various Planet orbits (Juhasz, An Analysis and Procedure for Determining Space Environmental Sink Temperatures with Selected Computational Results, 2001, p. 9)

Summary and Conclusions

The available materials in the solar system are virtually inexhaustible, but frequently are not in the locations needed. The moon, Mars, Mercury, Venus and the asteroids are fairly rich in metals and minerals, but lower in volatiles. Water is plentiful on some of the moons of Jupiter, Saturn, Uranus and Neptune, as well as comets, Kuiper Belt objects and in the Oort Cloud. Water is rare on Mercury, Venus and the Moon. Volatiles like Nitrogen are plentiful on Kuiper Belt objects like Pluto, as well as Titan and to a lesser extent Venus- but nonexistent on the moon and Mercury. To make use of the vast quantities of materials needed for the conquest of space will require transporting huge quantities of materials throughout the Solar System.

Energy is available both from sunlight, as well as mined nuclear materials. The sun's energy is free and virtually inexhaustible, but at the earth's distance from the sun, very diluted. Collectors for the capture of sunlight and the conversion into electricity will be necessary and used perhaps out as far as Mars. Nuclear energy is needed for more distant colonies.

Large space stations can be built in earth orbit in geosynchronous orbits, or at the L4/L5 points which are gravitationally stable regions.

To transport goods and materials objects will need to be put into elliptical orbits. The most efficient is called a Hohmann Transfer orbit, but these are fairly slow and therefore take a long time and will be most suitable for payloads and non-urgent supplies. People will likely need faster hyperbolic orbits. These will require either very high-performance rockets or, in some cases Oberth Powered Maneuvers using the sun or Jupiter.

Chapter 3 - Engineering and Physics Concept

Orbits

As we start developing our space infrastructure, we need to look at some of the characteristics of space travel, orbits and the techniques available for traversing in the Solar System.

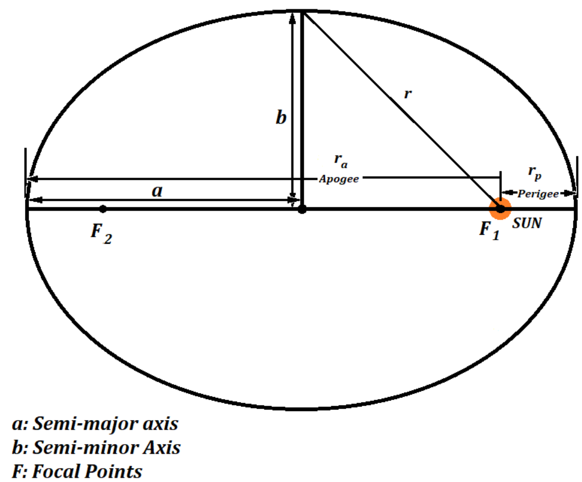


Figure 3-1

All objects in the solar system orbit in an ellipse around a large central mass (usually a planet or the sun). Elliptical Orbits have a periapsis (closest approach to the central planet, sun etc.) and an apoapsis (furthest point in the orbit)[1]. The characteristics of an orbit are shown in Figure 3-1. One key characteristic of orbits are that for any particular orbit, the total energy of the item, the sum of the Kinetic and Potential energy, is the same. As a planet or satellite approaches it apoapsis, it is slowing down and losing kinetic energy. However its potential energy is increasing as it is further from the gravitational center and has further to fall. The equations that describe this is as follows:

Equation 3-1 $$E_{total} = Kinetic\ Energy - Potential\ Energy = K_e - P_e$$

Equation 3-2 $$E = \frac{1}{2}mv^2 - \frac{GMm}{r}$$

Where:

M is the mass of the primary object

m is the mass of the orbiting object

$G = Gravitational\ Constant = 6.6743x10^{-11}m^3kg^{-1}s^{-2}$

v= velocity

r= distance from center of gravitational attraction

Sometimes the GM term is called the standard gravitational parameter and shortened to:

Equation 3-3 $\mu = Gm$

An orbital ellipse's properties can be easily calculated with a few additional equations. To identify the velocity of an object in a ellipse we use the equations:

Equation 3-4 $$v^2 = \mu(\frac{2}{r} - \frac{1}{a})$$

[1] Note that specifically when talking about orbits around the Earth, the comparable terms are usually referred to as Perigee and Apogee.

Or

EQUATION 3-5 $v(r) = \sqrt{(\frac{2\mu}{r} - \frac{\mu}{a})}$

Using the preceding equation if we assign the following:

$$r_P = Periapsis\ (in\ km)$$

$$r_A = Apoapsis\ (in\ km)$$

Transfer Semi Major Axis would be :

Equation 3-6 $a_{tran} = \frac{r_P + r_A}{2}$

Velocity at periapsis:

Equation 3-7 $v_p = \sqrt{\mu\left(\frac{2}{r_p} - \frac{1}{a_{tran}}\right)}$

Velocity at apoapsis:

Equation 3-8 $v_A = \sqrt{\mu\left(\frac{2}{r_A} - \frac{1}{a_{tran}}\right)}$

With these terms we can determine all the important parameters of our orbit.

Lagrangian points or Libration points

With the notable exception of moons around planets and minor planets, all other objects in the Solar System orbit the sun. All sufficiently massive bodies create what are called Lagrangian Points or Libration points. These are areas of relative gravitational stability, where objects, once placed there, can reside without quickly drifting away and will maintain their positions with little application of force. Outside of these Lagrangian points, objects will drift away quickly- disturbed by gravitational forces of other objects in the solar system. An object is placed at a Lagrangian point it will remain there indefinitely with little or no adjustment.

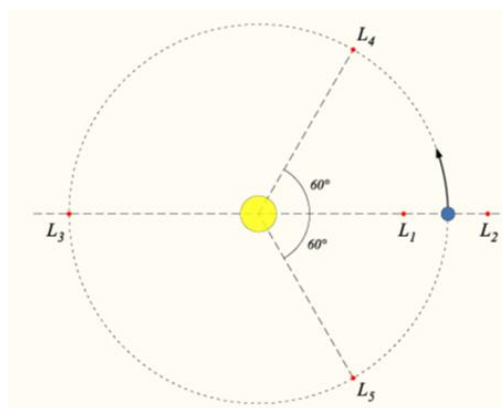


Figure 3-2

The L_3 and L_4 points are in the same orbit as the planet or moon and will be 60deg ahead or behind the orbiting body. For calculating the L_1 and L_2 points, we can use the approximate formulas:

Equation 3-9 $r_{L1} \sim R(1 - (\mu/3)^{\frac{1}{3}}$

Equation 3-10 $r_{L2} \sim R(1 - (\mu/3)^{\frac{1}{3}}$

Where:

Equation 3-11 $\boldsymbol{\mu = \frac{M_2}{M_1 + M_2}}$[2]

And M_1 is the mass of the large body that we are orbiting around. If we wanted to calculate the Lagrangian points for the earth, we would use the following:

$$M_1 = Mass\ of\ Sun = \ 1.989x10^{30}kg$$

M2 is the mass of the smaller body, in our case the Earth. The Earths Mass would be:

$$M_2 = Mass\ of\ Earth = 3.301x10^{23}kg$$

R is the distance between the earth and Sun or:

$$R = 1.496x10^{11}meters$$

This would give us an L1 and L2 points about 1.5 million kilometers on either side of the Earth.

Hohmann Transfer

This sort of maneuver is one whereby we go from a circular orbit to an ellipse with the perigee at our starting point and an apogee at our target distance. Usuaslly this is associated with traveling from one planet to another. Once we reach this apogee, we would then circularize our orbit at the new higher orbit by adding some velocity. The same technique can be used to get to a target at a lower orbit, except velocity (if traveling to another planet then our speed change would be relative to the sun) would be deducted to permit a lower perigee and once you get to your target orbit, velocity would need to be subtracted to circularize your orbit. A Hohmann Transfer trajectory is the minimal amount of energy you can use to get to your target and will rendezvous 180 deg from your starting point (opposite side of the mass you are orbiting). If we are going to Mars the Hohman transfer orbit would be an ellipse with the periapsis at the earth orbit, and apoapsis at Mars.

The Hohmann Transfer is the minimal energy needed to get to a target, but timewise will be the longest. Much faster transfers are possible but require much more energy.

We can calculate Hohmann transfer Δv's from the earth to get to various places in the Solar System and beyond. Table 3-1 shows some Hohmann transfer orbits from earth's orbit around the sun (i.e., like the L4 point in Figure 3-2). 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 reach interstellar targets on a hyperbolic trajectory. The reason of course is that the earth orbits at nearly 30kps and to reach the sun you would have to lose all this velocity.

---

[2] The term μ when used to calculate Lagrangian points is NOT the same as the standard gravitational parameter used in equation of orbital motion (equation 3-3). Unfortunately the same Greek letter is used!

[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.

Finally, Since Hohmann Transfer Orbits are an ellipse we can calculate the time as it is half the orbital period given by Keplers third law:

Equation 3-12 $\boldsymbol{t_{transfer} = \pi\sqrt{\frac{a_{tran}^3}{\mu}}}$

Where:

Equation 3-13 $\boldsymbol{a_{tran} = \frac{r_1+r_2}{2}}$

And from Equation 3-3 for the Sun:

$$\mu = GM_{\circ} = 1.327x10^{11}km^3s^{-2}$$

r_1 and r_2 are the distance from the sun in kilometers. If we calculate a Hohmann Transfer for Mars we would use:

$$r_1 = r_{Earth} = 149{,}597{,}871\ km$$

$$r_2 = r_{Mars} = 227{,}919{,}100\ km$$

$$a_{tran} = \frac{r_1 + r_2}{2} = \frac{149{,}597{,}871 + 227{,}360{,}000}{2} = 188{,}768{,}485\ km$$

We can solve then for $t_{transfer}$.

$\mathbf{t_{transfer}} = \boldsymbol{\pi\sqrt{\frac{(188{,}768{,}485)^3}{1.327x10^{11}}}}$**= 22367047 sec= 258.9 days**

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

Table 3-1 shows the velocity and transfer times to reach various targets in the Solar System. Note that transit times range from only a couple of months for Mercury (less than that required to reach Venus since the velocity change to lower our Hohmann Transfer periapsis so close to the sun is far greater than that for Venus) to on the order of 31 years to reach Neptune!!!

Planet	r2 (AU)	a (AU)	Transfer time (days)	Δv depart (km/s)	Δv arrive (km/s)	Δv total (km/s)
Mercury	0.387	0.6935	77.1	5.80	3.60	9.40
Venus	0.723	0.8615	112.0	2.94	1.54	4.48
Earth (same)	1.000	1.0000	365.3	0.00	0.00	0.00
Mars	1.524	1.2620	258.9	2.943	2.988	5.931
Ceres (2.767)	2.767	1.8835	434.6	5.15	1.42	6.57
Jupiter	5.203	3.1015	978.6	8.80	2.13	10.93
Saturn	9.537	5.2685	2,141.6	11.16	1.40	12.56
Uranus	19.191	10.0955	6,021.9	13.03	0.76	13.79
Neptune	30.071	15.5355	11,360.1	14.03	0.52	14.55
Pluto (39.48)	39.480	20.2400	18,011.0	14.46	0.40	14.86

Table 3-1 Hohmann Transfer Orbits from 1AU

These tables are simplified by many assumptions. As mentioned, planets orbit in ellipses and sometimes they are closer and other times further than the calculated distances. The table only shows average. In addition, we assume that all planets are in the same orbital plane as the earth- which is not true- especially for Pluto which orbits at an inclination of nearly 17deg. Furthermore, Table 3-1 assumes that we are leaving from an orbit around the sun at 1 AU. Instead we will be likely leaving from an earth orbit. To get into Earth orbit we already had to accelerate to around 8 kps. Table 15 would take into account the nearly 30kps orbital velocity, but it would not take into account the 8kps orbital velocity, nor the partially offsetting requirement to escape the Earths gravitational well. Calculating the dV to leave the earth's gravity would be done by calculating a hyperbolic trajectory dV for the earth and then adding the 8 kps for the earth's orbital motion, assuming that we do these maneuver's while facing in the desired direction (see Fig 3-3). Overall, these two effects will reduce the required dV by a few kps from those shown above.

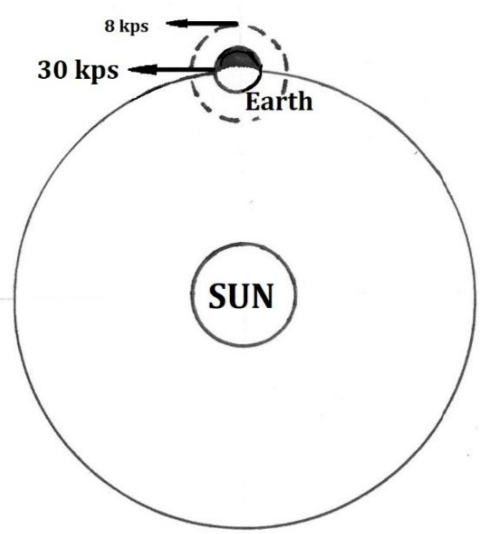


Figure 3-3

Table 3-3 also has left off the need to get into orbit around the target planet. In this chart the spaceship will arrive at the target planets (or asteroid) going at a different speed than the planet. The dV arrive accounts for putting a spaceship into an orbit the same distance from the sun. However we will likely want to be captured by the planet so additional dv may be needed to go into orbit. This is reflected in the numbers in Table 16. These numbers were calculated using a capture radius of about 300km above the visible surface of the target planet. The formula used to capture the spacecraft is:

Equation 3-14 $dv_{Capture} = v_{hyp,peri} - v_{cir,peri} = \sqrt{v_\infty^2 + (2\mu_p)/r_{par}} - \sqrt{\mu_p/r_{par}}$

To calculate the actual dV from LEO, we pick Mars for an example:

- **Earth:**
  - **Radius:** $R_E = 6378$ km
  - **Gravitational parameter:** $\mu_E = 398600 \text{ km}^3/\text{s}^2$
  - **LEO radius:** $r_{LEO} = R_E + 300 = 6678$ km
  - **LEO circular speed:** $v_{c,E} = \sqrt{\mu_E / r_{LEO}}$
- **Sun / heliocentric:**
  - **Earth orbital radius:** $r_E = 1$ AU
  - **Mars orbital radius:** $r_M \approx 1.524$ AU
  - **Earth orbital speed:** $v_E \approx 29.78$ km/s
  - **Mars orbital speed:** $v_M \approx 24.07$ km/s
  - **For a Hohmann transfer, the semi-major axis is $\boldsymbol{a_t = \frac{r_E + r_M}{2} \approx 1.262}$ AU**
- **Mars:**
  - **Radius:** $R_M = 3396$ km
  - **Gravitational parameter:** $\mu_M = 42828 \text{ km}^3/\text{s}^2$
  - **LMO radius:** $r_{LMO} = R_M + 300 = 3696$ km
  - **LMO circular speed:** $v_{c,M} = \sqrt{\mu_M / r_{LMO}}$

Step 1: Heliocentric Hohmann transfer impulses and hyperbolic excess speeds

The Hohmann transfer velocities at Earth's and Mars' orbital radii are:

$$v_{t,E} = \sqrt{\mu_\odot \left(\frac{2}{r_E} - \frac{1}{a_t}\right)}, v_{t,M} = \sqrt{\mu_\odot \left(\frac{2}{r_M} - \frac{1}{a_t}\right)}.$$

The heliocentric impulses are:

$$\Delta v_1 = v_{t,E} - v_E, \Delta v_2 = v_M - v_{t,M}.$$

Numerically (standard values):

- **Departure impulse:** $\Delta v_1 \approx 2.94$ km/s.
- **Arrival impulse:** $\Delta v_2 \approx 2.65$ km/s.

For a prograde, coplanar departure/arrival, these impulses correspond to the required **hyperbolic excess speeds** relative to the planet:

$$v_{\infty,E} \approx \Delta v_1 \approx 2.94 \text{ km/s}, v_{\infty,M} \approx \Delta v_2 \approx 2.65 \text{ km/s}.$$

Step 2: Burn from 300 km LEO to trans-Mars injection

Compute the circular speed in 300 km LEO:

$$v_{c,E} = \sqrt{\frac{\mu_E}{r_{LEO}}} = \sqrt{\frac{398600}{6678}} \approx 7.73 \text{ km/s}.$$

Perigee speed on the Earth-departure hyperbola that yields $v_{\infty,E}$:

$$v_{p,E} = \sqrt{v_{\infty,E}^2 + \frac{2\mu_E}{r_{LEO}}} = \sqrt{(2.94)^2 + \frac{2 \cdot 398600}{6678}} = \sqrt{8.64 + 119.34} \approx \sqrt{127.98} \approx 11.31 \text{ km/s}.$$

Thus the trans-Mars injection burn from LEO is:

$$\Delta v_{TMI} = v_{p,E} - v_{c,E} \approx 11.31 - 7.73 = 3.58 \text{ km/s}.$$

Step 3: Mars orbit insertion to 300 km LMO

Compute the circular speed in 300 km LMO:

$$v_{c,M} = \sqrt{\frac{\mu_M}{r_{LMO}}} = \sqrt{\frac{42828}{3696}} \approx \sqrt{11.59} \approx 3.41 \text{ km/s}.$$

Periapsis speed on the Mars-arrival hyperbola for $v_{\infty,M}$:

$$v_{p,M} = \sqrt{v_{\infty,M}^2 + \frac{2\mu_M}{r_{LMO}}} = \sqrt{(2.65)^2 + \frac{2 \cdot 42828}{3696}} = \sqrt{7.02 + 23.18} \approx \sqrt{30.20} \approx 5.50 \text{ km/s}.$$

Mars orbit insertion burn (single impulse to circularize at periapsis to 300 km):

$$\Delta v_{MOI} = v_{p,M} - v_{c,M} \approx 5.50 - 3.41 = 2.09 \text{ km/s}.$$

Step 4: Total delta-v from 300 km LEO to 300 km LMO

Add the major impulses (excluding mid-course corrections):

$$\Delta v_{\text{total}} \approx \Delta v_{TMI} + \Delta v_{MOI} \approx 3.58 \text{ km/s} + 2.09 \text{ km/s} = 5.67 \text{ km/s}.$$

Repeating for other solar system bodies we get Table 3-2.

Body	Distance from Sun (AU)	Δv LEO departure (km/s)	Δv orbital insertion (km/s)	Total Δv (km/s)	Avg. transit time
Mercury	0.387	5.53	7.51	13.04	~106 days
Venus	0.723	3.48	3.33	6.81	~146 days
Mars	1.524	3.59	2.09	5.68	~259 days
Ceres	2.77	4.89	4.60	9.49	~1.30 years
Jupiter	5.204	6.29	17.70	23.99	~2.73 years
Saturn	9.58	7.27	10.91	18.18	~6.08 years
Uranus	19.2	7.96	6.65	14.61	~16.0 years
Neptune	30.05	8.24	7.12	15.36	~30.6 years
Pluto	39.48	8.39	3.08	11.47	~45.5 years

Table 3-2

Several issues become apparent when looking at the above chart. Frequently the dv needed for a Hohmann transfer is relatively small, but the dv for capture is frequently as big or even bigger. For small objects like Ceres we require about dv of 4.9kps. However, to slow down and be captured requires an additional 4.6kps. It is probably reasonable to assume that to land on most asteroids a total dv of 10kps will be required.

For the larger objects (like Jupiter and Saturn) these numbers are so large because they are calculated to slow an object down so it can go into orbit at 1000km above the cloud tops. If we were to pick a more distant orbit (for instance one where their moons are) the numbers will be much lower. Indeed, in the case of direct approach to Titan, the approach speed can be slow enough that a TPS will be more than enough to permit entry as we will approach Titan between 5.5-8kps, and only a short landing burn would be required. This means that a mission and landing on Titan would require only about 7.5-8kps of dv- though the transit time of 6+ years would be challenging.

If we can use aerobraking at a planet with an atmosphere, the dv frequently will be close to the dv required for LEO departure. Of course this is only applicable to bodies with a substantial enough atmosphere to impart the required deceleration.

These calculations can get much more involved if we are talking about the moons of a large planet like Jupiter. Since they are also orbiting around their planet we can approach a moon from the proper direction to minimize the dv required for capture. However, as opposed to Titan, Jupiters moons do not have an atmosphere and as mentioned we could not use Jupiter or Saturn to aerobrake… the approach speeds are too high for a Thermal Protection System (TPS) to handle.

There are several simplifying assumptions made- these calculations are for the average distance from the sun so the actual transfer times may be a little more or less depending on the planets location. This also assumes that the Earth LEO and planet are all lined up in a plane- the reality is that planets may be at slightly higher or lower angles from the earths' orbital plane- in the case of Pluto- it is a very high 17degrees.

Oberth 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 dv 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:

EQUATION 3-15 $V = \Delta v\sqrt{1 + (\frac{2V_{esc}}{\Delta v})}$

Where

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

Δv= delta v of burn at periapsis

V_{esc}= escape velocity at periapsis

Using our previous equation for esc velocity:

EQUATION 3-16 $v_{esc} = \sqrt{(\frac{2\mu}{r})}$

Recall that $\mu = GM$ and

$$G = 6.672x10^{-11}\frac{Nm^2}{kg}$$

For some representative numbers, the Earth Mass is 5.972 x 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.

Calculating for $\mu_{Jupiter} = GM_{Jupiter} = 6.6743x10^{-11}x318(5.972\text{x}10^{24}) = 1.2675x10^{17}$

Calculating for $\mu_{Sun} = GM_{Sun} = 6.6743x10^{-11}x333{,}000(5.972\text{x}10^{24}) = 1.3273x10^{20}$

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.

$$v_{esc} = \sqrt{\frac{\mathbf{2(GM_{Jupiter})}}{\boldsymbol{r}}} = \sqrt{\frac{\mathbf{2}(1.2675x10^{17})}{75{,}600{,}000}} = 57{,}906mps\ (57.9kps)$$

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

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

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 Vesc) 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 3-3

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 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.

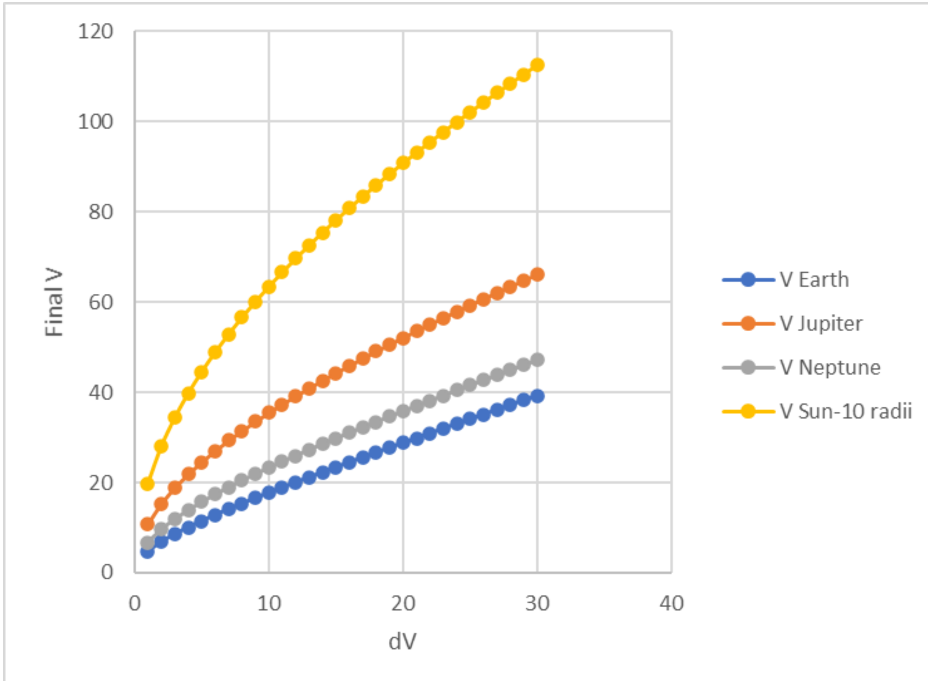


Figure 3-4 Oberth Powered Maneuver (Note that in these calculations the Periapsis Distance from the center of the body was- Earth- 7000km; Neptune 28,000km; Jupiter 75,600km; Sun 6,757,000km).

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 Vesc. 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:

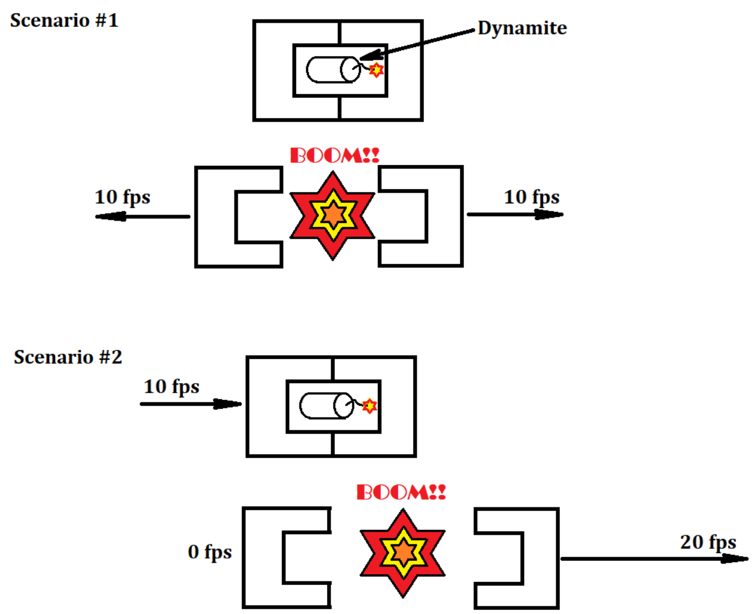


Figure 3-5 Oberth Maneuver Explanation

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

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 decreased (the rocket exhaust is slower compared to the sun) but it transferred its KE to the rocket.

The Oberth maneuver will be limited in its application. It requires high thrust rockets and requires extensive maneuvering to approach a high gravity body. I can see the Oberth maneuver being of most use to send rapid voyages to the outer solar system. In this case, a few years and a few orbital adjustments that bring an object close to the sun may be worth the extra dv incurred.

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

Typical Velocities and Transit Times

Table 3-4 showed some typical dv's and their associate transit times for a spaceship following a minimal energy Hohmann Transfer orbit from LEO (300km) and to do an orbital insertion at the target of 1000km above the visible cloud layer for the giant planets. Note that in many instances going into orbital insertion is not practical or desirable especially at the giant planets. We will not need to go into orbit and have no ability to land on their surfaces. Instead we would want to land on their moons. In all cases, their moons are much further from the planets gravity well so going into an orbit where a moon is will be far easier. Furthermore, if we time our approach correctly we will rendezvous with the moon in the part of its orbit that will minimize our approach speed. In many cases for Jupiter and Saturn, our actual dv needed on arrival would be between 3-7 kps.

Body	Distance from Sun (AU)	Δv LEO departure (km/s)	Δv orbital insertion (km/s)	Total Δv (km/s)	Avg. transit time
Mercury	0.387	6.53	8.90	15.43	~92 days
Venus	0.723	4.48	3.95	8.43	~132 days
Mars	1.524	4.59	3.40	7.99	~190 days
Ceres	2.77	5.89	5.65	11.54	~1.15 years
Jupiter	5.204	7.29	18.90	26.19	~2.45 years
Saturn	9.58	8.27	12.10	20.37	~5.45 years
Uranus	19.2	8.96	7.35	16.31	~14.2 years
Neptune	30.05	9.24	7.85	17.09	~27.0 years
Pluto	39.48	9.39	3.45	12.84	~40.0 years

Table 3-4

Depending on the rockets purpose (passengers or cargo), where the rocket is departing from Earth orbit, whether the rocket is in a Solar Orbit, a Lagrangian point (around the Earth or some other body) and what we want to do when we get to our target (land, atmospheric capture if an atmospheric is available, or some other permutation/combination) will drive the velocity required. At the very least, a leisurely voyage to anywhere but to the moon will require dVs of 5-8kps. Times can be reduced with higher speeds- hyperbolic trajectories are traveling so fast that they will escape the solar system. If we double the velocities, we would more than half the transit time- so that as an example, a mission to Jupiter leaving at 15kps would only take a little more than a year to arrive. However, when reaching Jupiter the spacecraft would be traveling so fast that it would need to perform a very large additional dV to be captured by the planet. Otherwise, the spacecraft would continue its hyperbolic trajectory and leave the solar system.

Realistically, we shall see that giving a spaceship the ability to do a dv of 15 or 20kps is difficult and may not be practical until some fundamental improvements to nuclear propulsion are developed.

Suppose we incrementally increase our spaceship capabilities by a more realistic amount so that we increase our departure dv by 1kps over and above that calculated for a Hohmann Transfer from LEO. Table 3-5 shows us the new dvs and new Transfer Times. As can be seen, the 1kps dv increase in departure velocity increased the dv for orbital insertion by more 1kps.

With just a slight increase in departure speed, we have drastically reduce our transit times.

Body	Distance from Sun (AU)	Δv LEO departure (km/s)	Δv orbital insertion (km/s)	Total Δv (km/s)	Avg. transit time
Mercury	0.387	7.53	9.90	17.43	~78 days
Venus	0.723	5.48	4.60	10.08	~118 days
Mars	1.524	5.59	3.95	9.54	~165 days
Ceres	2.77	6.89	6.30	13.19	~1.00 years
Jupiter	5.204	8.29	20.10	28.39	~2.20 years
Saturn	9.58	9.27	13.40	22.67	~4.8 years
Uranus	19.2	9.96	8.10	18.06	~12.7 years
Neptune	30.05	10.24	8.65	18.89	~23.5 years
Pluto	39.48	10.39	4.00	14.39	~34.0 years

Table 3-5 Faster than Hohmann transfers- add 1kps to depature speed over Hohmann transfer.

All these velocities will just allow our spaceship to be captured into the planets orbit. For those planets that we want to land on we will need an additional dv- that may add another 1-2kps. The exceptions are those bodies with an atmosphere which for Mars, Venus, and as discussed Titan, essentially eliminate the dv for orbital insertion. This aerobrake technology, as well as the planets atmospheric density and composition will determine effectively how much dV can be shed this way, but up to 7kps may be achievable for Mars, Venus or Titan. Aerobraking for a Titan mission means that the dV requirement to go to Titan is less than landing on an airless asteroid like Ceres and much less than landing on a moon like Ganymede

Another limitation is that the figures above are to be captured by these planets, but in the case of the gas giants, we will trying to land on their moons. Since without exception, the moons orbit much further than the calculated 1000km above the cloud tops, our dv will be much less than shown for Jupiter or Saturn frequently closer to the numbers shown in Table 10. Offsetting this somewhat is the fact that for the airless moons like Ganymede or Callisto, we would need to add another 2-3kps of performance to be able to land on their surfaces. The actual total minimal required dv to land on Ganymede would be about 11-14 kps.

One of the major issues with all of the tables is that we can see that unless we are going far faster than the ideal Hohmann Transfer orbits, our mission timelines are very long to anywhere in the solar system except for the moon and Mars. To get missions to the outer planets down to months or at most a couple of years for Neptune, we would be looking at total dVs 10x greater than what we have considered- on the order of 100kps.

Table 3-6 broadly summarizes some rules of thumb for objects launched from low earth orbit. We can see that Aerobraking is particularly helpful for Mars and Titan. Indeed, landing on Titan is almost impossible without it. Note these calculations for orbital insertion assume we are entering a 300km orbit around the rocky bodies, and 1000km above the cloud tops for the larger gas giants. In reality, if we were approaching one of the moons of Jupiter or Saturn, we would be much further out, reducing our required dV. This is very fortunate for Titan as our TPS system should be robust enough to permit a direct Titan entry .Below we have summarized some of the highlights and broken out our dv needs into three categories: under 10kps, 10-13kps, and above 13kps.

	dV	Transit Times (Hohmann Transfer)
Moon	6	1-2 days
Mars (orbit)	8	8.5 months
Mars with Aerobraking	5	8.5 months
Asteroids (Ceres, Vesta)	10-14	1-2 years
Jupiter (Ganymede)	13+	2.5 years
Saturn (Titan with Aerobraking)	7.5	5.5 years
Neptune (Triton)	12kps with Neptune Aerobrake 18kps without Aerobrake	27 years
Pluto	12	40 years (will vary depending on orbital location)
Eris	12-14	70 years (will vary depending on orbital location)

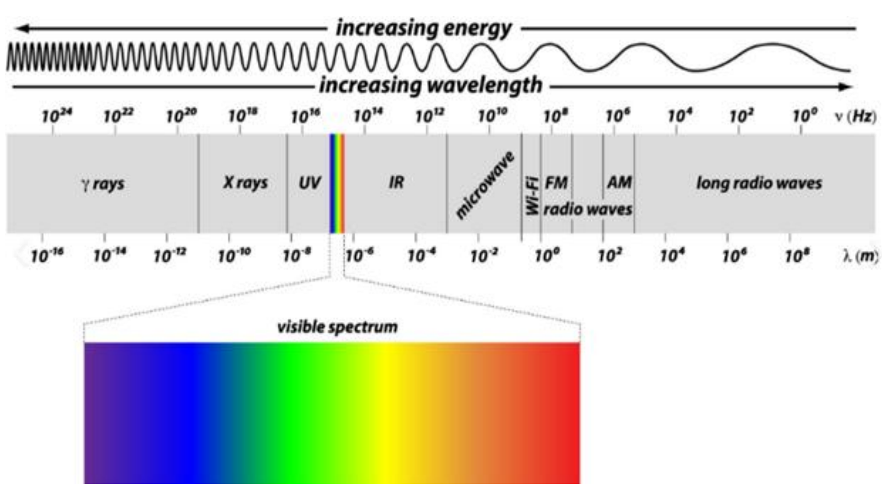
Table 3-6 Minimal Required Spacecraft Performance.

In green, I highlighted objects that can be reached with 10kps or less dv. These are within the capabilities of some of the interplanetary spaceships currently in design. In Yellow are those between 10.1 and 13kps. Finally, in red are those objects that consistently need more than a 14kps dv. Except for the moon, Mars, and some asteroids, any direct to target mission will need more than 10kps.

In addition to aerobraking, there may be other techniques that could facilitate spacecraft missions- including gravitational slingshots and the Oberth powered maneuver discussed in Chapter 2 and momentum transfer technology that will be addressed in Chapter 6.

Communications and Beamed Power with Microwaves and Laser

Spacecraft and colonies will need to communicate via electromagnetic radiation- radio, microwave or laser light. Electromagnetic radiation are photons, small energy packets that travel at the speed of light at a specific frequency. The frequency of photons is a measure of how quickly the photons oscillate, and can be represented on the electromagnetic spectrum (see Figure 3-7) where low frequencies are called radio waves, and high frequency would be Gamma and X rays. The number of photons passing through a particular area in an interval of time determines its strength or intensity.



Electromagnetic (EM) radiation can be used to carry information either by varying the frequency (ie. FM Radio) or

Strength/Amplitude (ie. AM Radio). Even more importantly, EM radiation carries energy. Sunlight warms the planet and provides the energy for plants to grow. We will investigate throughout this book some uses that can be made by beaming power but before then we need to review some of the principles of electromagnetic radiation.

It is a property of all forms of electromagnetic radiation, including radio waves, microwaves, visible light and x-rays, that a transmitted beam will spread out over distance. How quickly a beam spreads out is determined by two factors- the wavelength of the electromagnetic radiation, and the diameter of the source. The same physics that drive this concept are seen with radio transmitters- the only difference is that radio waves are much longer (see Figure 3-7.

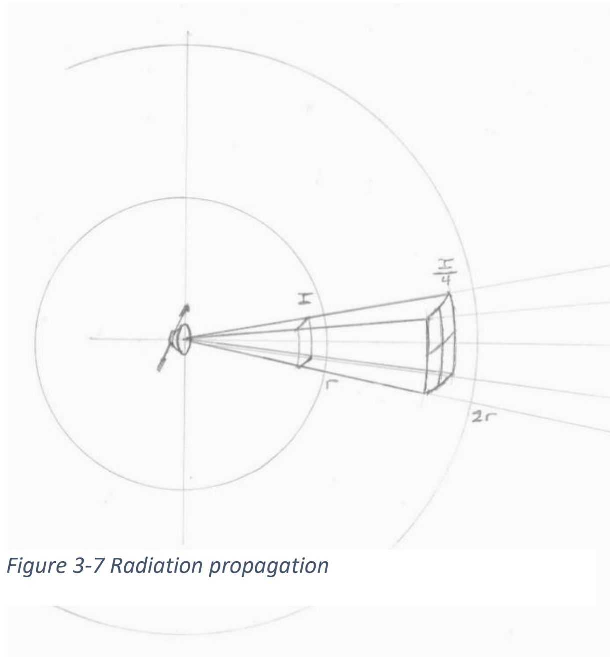


Figure 3-7 Radiation propagation

The simplest transmitters, be it a radio station antenna or a light bulb, emit their radiation out spherically in all directions, with only a very small amount of the photons actually reaching the receiver. A flashlight with its reflective lens, as with a parabolic dish for a radio transmitter, significantly improves upon this by directing the beam in (mostly) one direction (called coherent). However it is impossible to totally prevent a beam from spreading, no matter how large or finely designed a transmitter is.

One interesting and powerful technology that could be useful for our colonization infrastructure is beaming power across the solar system via microwaves or laser light. A large powerplant, either solar or nuclear, would send out electromagnetic radiation (either as microwave's as we will see with the Space Based Solar Power Plant (SBSPS) in chapter 12, or light via laser and a receiver would convert this radiation to electrical energy- in the case of microwaves, with about 85% efficiency, and in the case of laser light, with a properly "tuned" receiver, perhaps as high as 50%. Creating and converting microwave energy is more efficient, and microwaves are easier to steer than laser light, but lasers provide a more coherent beam and can be beamed much further. Furthermore, mastering the technology of powerful laser beaming may be a way of improving the practicality of solar sails by substituting the relatively low energy from the sun further out in the solar system with a much more concentrated source (Chapter 6).

Raleigh Criterion

We can improve upon the theoretical performance and tighten our beam within the constraints of physics. A beams divergence was figured out by the scientist Lord Raleigh (born John William Strutt) who came up with a simple formula that we now call Raleigh's criterion which states:

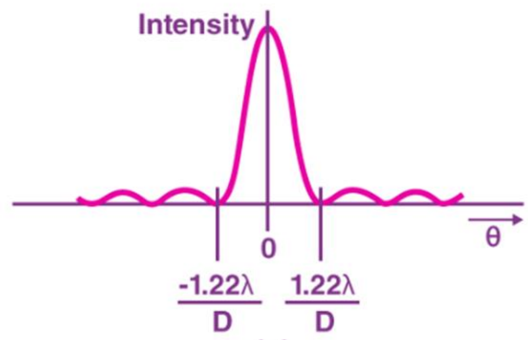


Figure 3-8 Raleigh Criteria

EQUATION 3-17 $Sin\theta = 1.22\frac{\lambda}{d}$

Where:

$\lambda = wavelength$

$d = diameter\ of\ the\ transmitter$

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

EQUATION 3-18 $\theta = 1.22\frac{\lambda}{d}\ (in\ radians)$

Figure 3-8 shows graphically the signal strength vs angle θ. What Equation 3-17 tells us is that the tightness of the beam depends on only two parameters- the diameter of the transmitter and the wavelength of the electromagnetic radiation. 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 3-6 that the wavelength of visible laser light is around $5x10^{-7}$ meters. If one has the frequency of a radio or light wave, one can easily calculate the wavelength with the formula:

EQUATION 3-19 $\lambda = \frac{c}{f}$

Where:

$c = speed\ of\ light\ (3x10^8 mps)$

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

Why would we want to beam power through the solar system? As on earth, our sources of power are frequently distant from where they are needed. On Earth, power lines transfer this power frequently over hundreds of miles. Beamed power would serve the same function as power lines on earth. Most colonies and large Space Stations will want to have a local power supply, but we can easily conceive power stations beaming down their power to earth, the moon, or to interplanetary spacecraft. Beaming power through the solar system has several advantages. It could replace the need to carry a large power supply, especially on spaceship where heavy dead mass restricts velocity. On a spaceship that mass can be minimized be reduced to perhaps only 25% of the mass of carrying a nuclear power plant or large solar panels (see Chapter5).

Strengths and Properties of Materials

Throughout this book we will look at designing spaceships, space stations and colonies. To create realistic designs we will have to use materials that are available throught the solar system. The characteristics of materials will determine what designs are feasible and practical. Prevalence will also play a role. It will not be economically feasible to build a space station of a material that is not available. When picking a material we need to weigh the pros and cons and select the best we can. This involves looking at some characteristics:

- Material Properties
    - Tensile strength
    - Compressive strength
    - Mass/Density
    - Operating Temperatures
- Ease of manufacture (how much energy and how hard is it to create and form?)
- Flexibility and Ease of use (can it be stamped, welded, bent?)
- Durability (does it meet the durability requirements for the purpose it is being used?)
- Prevalence (is it available? How easy is it to mine?)
- How easy to refine? (how hard is it to separate the required materials from other elements?)

In chapter 2 we looked at the availability of the raw materials. In this chapter we will look at some typical material properties like Tensile Strength, Compressive Strength, Density and Operating Temperatures. In chapter 10 we will look at how to mine and transport materials throughout the Solar System.

The primary characteristics of a material are their compressive, tensile, density and operating temperatures. Table 3-7 shows some of the most common structural materials that would be used in space construction. We will use other materials, but they will be primarily for radiation and impact protection (i.e., regolith, dirt, water ice) where bulk and not structural strength is the primary requirement.

Material	σ_t Yield Tensile Strength MPA	Compressive Strength	Density	Operating Temperature	Comments
Aluminum	240-275		2700	-50 to 150	
Titanium	275-880		4500	-200 to 400	
Steel	250-450		7850	-200 to 400	
Stainless Steel	275-290		7750-8000	-200 to 870	
Carbon Fiber	400-4000		1550-1950		Does not yield; brittle failure

Table 3-7

Since most human habitation structures will be pressurized with an atmosphere, compression strength will usually be less important than Tensile Strength. Operating temperatures will generally be important for reentry vehicles which can be subject to high heat loads. Operating temperatures may also play a factor in equipment near Mercury, where solar radiation is intense. Most space structures will operate in environments of extreme cold, but as we will see environmental cold will not be a factor in most cases (tanks storing cryogenic materials being an exception).

Other important properties when selecting materials and building structures can be shown on a Stress Strain curve (Figure 3-9). When you apply a load or force (stress) to a ductile material (most metals) will deform (strain) by stretching out (the straight line (O-A) in the figure). In this region, if you double the load you will double the deformation. If the load is removed the metal will return back to its original dimension (O). If you go past A to a region between A and B and then remove the load, the metal will

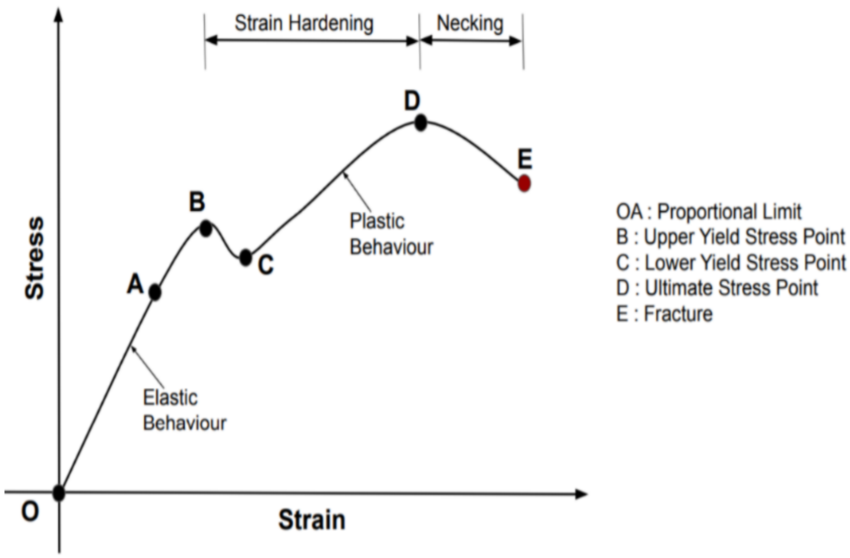


Figure 3-9

shrink back somewhat, but never all the way back to O… instead it will be permanently deformed. As you put a further stress the material will temporarily lose it strength (and start stretching further) as its internal atomic structure reorganizes. Past C the material exhibits plastic behavior where it continues to get stronger but it also is permanently deforming. After D the material will fail as it starts deforming even as the load starts decreasing.

The stress strain curve is very useful in helping to determine what materials we would want to use. Every metal has its own stress strain curve. The point from O to A is defined by the formula:

Equation 3-20 $E = \frac{\sigma}{\varepsilon}$

Where:

$E = Youngs\ Modulus \backslash \sigma = Stress\ (force\ per\ unit\ area)\ in\ Megapascals\ (MPa)$

$\varepsilon = Strain\ (dimensionless) measuring\ change\ in\ length\ vs\ original\ length\ (expressed\ as\ a\ \%)$

We can also come up with rules of thumb with regards to bending a material. As with a tensile load, metals can be bent and when the load is removed, go back to shape. However if a material is bent past its deformation limit it will remain permanently bent. The maximum bending strain for a thin sheet is:

$$\varepsilon_{max} = \frac{t}{2R}$$

Where:

$$t = thickness\ of\ sheet\ (in\ meters)$$

$$R = Radius\ (in\ meters)$$

Rearranging the terms to solve for $R_{elastic}$:

$$R_{elastic} \geq \frac{t}{2\varepsilon_y} = \frac{tE}{2\sigma_y}$$

We would get E and σ_y from a table of material properties. For instance, if we use Stainless Steel we can use E= 200 GPa, and $\sigma_y = 205 MPa$ and if we assume a thickness of 4mm (.004m) then solving for R we would come up with a minimum acceptable radius of 2.35 meters. We would probably want to increase this to have some margin. Note that 4mm is the thickness of the SpaceX Starship shell so this implies the steel could spring back if released (cut off) from its structure. However the steel is provided in rolls that may already exceed the elastic limit. Furthermore the stainless steel may be cold rolled before used on the structure and this could make the Stainless Steel permanently deformed.

Heating and Cooling in Space

Space is a vacuum which makes it surprisingly hard to remove heat. Every joule of energy generated within the spaceship must be removed to keep the spaceship or space station from overheating. In the case of a spaceship, some of this energy will be removed via the energy expelled by the propulsion system, be it chemical, thermal or electric. However, most heat generated via a nuclear powerplant in a spaceship in a space station must be removed or else the spaceship will keep warming up.

An additional factor is proximity to a sun or even a planet. The suns surface temperature is 5780C. The space around the solar system is about 2.7C. The further you get from the sun the lower your temperature will be because the sun is a smaller and smaller part of the sky, and the greater amount of area is covered by the low temperatures of deep space. However, if we are very close to the sun our materials directly exposed to its radiation may reach temperatures so high that they weaken or fail. Conversely, near the sun it will be difficult to remove heat from our spaceship. The same applies to a lesser degree when we orbit a planet in a spaceship or space station. If a spacecraft is orbiting a planet it will experience the heat of the sun but also the heat of the planet from reflecting heat from the sun, or re-radiating heat that its surface has gained. Either way, all planets in the solar system, even Neptune, will be far warmer than deep space. This needs to be factored in when figuring out how easy it will be to cool a space station or spaceship down.

Using the Stefan Boltzmann equation, we can calculate the temperature of an object a certain distance from the sun. The Equation for calculating temperature a certain distance from the sun is:

EQUATION 3-21 $$T_T^4 = \left(\frac{R_\odot^2 T_\odot^4}{4R_T^2}\right)$$

Where T_T = temperature of our Target and R_t is the radial distance to our target.

σ is the Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^{2}K^4)

R_Θ is the radius of the sun in meters. This is 696 x 10^6 m

T_Θ is the temperature of the sun in Kelvin. The surface temperature of the sun at R_Θ is 5780K

R_T is the distance of the earth from the sun- or about 1.496×10^{11} m. CC

Rearranging and simplifying we get the equation:

EQUATION 3-22 $$T_T = T_\odot \sqrt{\left(\frac{R_\odot}{2R_T}\right)}$$

To determine how easy it is to cool an item we need to figure out how much heat it will radiate. The equation for this is:

EQUATION 3-23 $$\Phi_e = A_i \epsilon \sigma (T_{rad}^4 - T_{sink}^4)$$

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 blocking screen.

Suppose we wanted to calculate the surface area required to get rid of 1 MW of power? Rearranging our terms:

EQUATION 3-24 $A_i = \frac{\Phi_e}{\epsilon\sigma(T_{rad}^4 - T_{sink}^4)}$

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_{sink} = 20k. 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, An Analysis and Procedure for Determining Space Environmental Sink Temperatures with Selected Computational Results, 2001)

σ_{sb} is a derived constant = $5.67*10^{-8}$ Wm^2K^4

We will assume a radiator temperature of 150 C (423K). Filling in our equation we would get:

$A_i = \frac{3{,}000{,}000}{.9(5.67x10^{-8})(423^4 - 20^4)}$=1836 m^2 or a square about 42.9 m on a side.

EQUATION 3-25 $L_{\odot} = 4\pi R_{\odot}^2 \sigma T_{\odot}^4$

Where:

$L_{\odot}$ is the suns luminosity.

To determine the temperature at a different distance from the sun we can use the equation:

Rearranging and simplifying:

EQUATION 3-26 $T_T = T_{\odot}\sqrt{(\frac{R_{\odot}}{2R_T})}$

For our structure at L1 R_T distance (as with a Solar Occulus- Chapter 12) from the sun will be about 148,500,000 km. Substituting

$$T_T = 5780K\sqrt{(\frac{6.96x10^8}{2 * 1.485x10^{11}})}$$

T_T= 279.8K

We are actually even cooler than this. If we assume 80% reflectivity (20% absorption) we have:

$(.2)^{.25}$ = .56

or only 56% of the temperature- or only 157.33K.

Chapter 4 - Human Needs in Space

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, this side will get 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 easily available resources required by a person to survive. Some examples:

- Air and Water
- 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 deadly cosmic radiation which frequently come from supernova, neutron stars or black holes. Nearer to the sun or another star you will get a large amount of photons as well as 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 (say with a pump) without the atmosphere 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- an extremely painful process that mercifully will kill you swiftly.

After providing a person with 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 and near a star. Without an insulated and an appropriately heated or cooled suit, death will likely result within an hour.

The third most critical requirement is water, without which the astronaut would expire within a few days. Some solar system bodies have very large quantities of water (Ganymede, Callisto, Titan), usually frozen. Other locations have little or no water (like the moon or Venus).

The fourth big requirement is food or nutrition. To survive for weeks or months the astronaut would need calories in the form of sugars, but also protein, vitamins and minerals. These need to be brought along or grown, which itself is problematic.

A fifth requirement is power. It may seem obvious but to be able to keep our astronaut warm, or to cool him or her down, as well as to provide light to operate in or to grow food, power is needed. Throughout this book we will look at various sources of power. As with water, a few days without power and the 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 on 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 over long term. Without gravity our bones lose calcium and gradually become 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 pose serious health consequences.

The eighth risk, though 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 fortunately 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 damaging equipment or puncturing a hull.

We will look at all these requirements throughout this book. All manned spacecraft over the last 50 years have different means of addressing the first five items and some have also addressed the eight item. 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 has been seriously addressed but the risks are known and engineering and technological fixes are available. Meteroid protection has occasionally been addressed but more robust solutions need to be implemented- which we will also discuss.

Air

Humans can live and thrive in oxygen levels and atmospheric pressures lower than sea level with only a short period of acclimation. By increasing the ratio of oxygen levels, pressures as low as 50% of sea level can also be managed by most people- but the risk from fire will increase and since flammability is mostly associated with oxygen concentration. This risk will have to be managed.

All breathable air (oxygen and nitrogen) for all space missions to date has been brought up from the earth. Sea level pressure on earth is 1013 kilo Pascals(kPa) or 1013 mbars (14.7psi). Most people can comfortably live at levels only 80% of sea level- the pressure at about 2000m above sea level, or only slightly less pressure than experienced in Denver or slightly more than experienced in Mexico City. In addition, we can survive 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 gases like Xenon, CO_2, 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 210mbar, humans can survive, but at this low pressure there are other risks. At 210mbar, breathing efficiency decreases while the fire risk greatly increases, atmospheric humidity is very low and uncomfortable, and sound does not carry.

All of the early NASA missions, including Apollo, compromised and used a pure oxygen atmosphere to 340mbar (5psi), but this was determined to be the lowest total pressure that was acceptable for long term. Skylab kept this low pressure but added an inert gas of 30%, leading to a lower oxygen partial pressure of around 200mbar- or just slightly below the sea level partial pressure (see Figure 4-2).

There are several advantages in using these very low pressures. It saves weight, partly because it eliminates the need to carry (and store) nitrogen. Reducing the pressure on your spacecraft allows your vessel pressure hull to be lighter- thinner metal walls and less structural reinforcement- though this may not be as big as an influence as you might imagine. 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 hitting a wall. With that being said, the lower pressure does allow for a less robust structure and will reduce mass. A robust structure becomes more important for larger spacecraft designed to have people in it for years or centuries. The structural loads on a very large spacecraft are 3x greater at 1bar vs 340mb- and the wall or shell thickness (as we shall shortly see) becomes much larger.

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 a spacecraft with 10,000m^3 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 (and therefore your mass) will be about half.

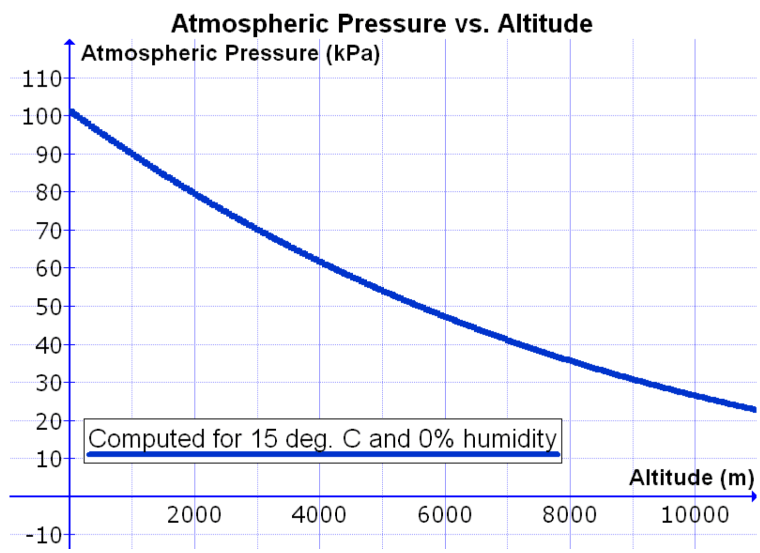


Figure 4-1 Atmospheric Pressure vs Altitude

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 operate at low pressure and with 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. However, for a long mission or for a space station that is permanently inhabited, it is unlikely that the astronaut will ever need to go into space in a space suit so this advantage is negated.

One serious problem with low pressure is a greater proportion of Oxygen. In a 100% oxygen environment fires become more dangerous. Above a certain level, pure oxygen causes a decrease in lung functioning and inflammation. Pure oxygen is both corrosive and very reactive. 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 need to shout to be heard. A larger spacecraft or a artificial colony, where the area 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, the air is 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.

NASA has issued guidance for atmospheric composition based on the risks of Hypoxia (to little oxygen), Hyperoxia (too much oxygen) and Fire Risk (Headquarters, NASA-STD-3001 NASA Spaceflight Human System Standard= Volume 2: Human Factors, Habitability, and Environmental Health, 2025).

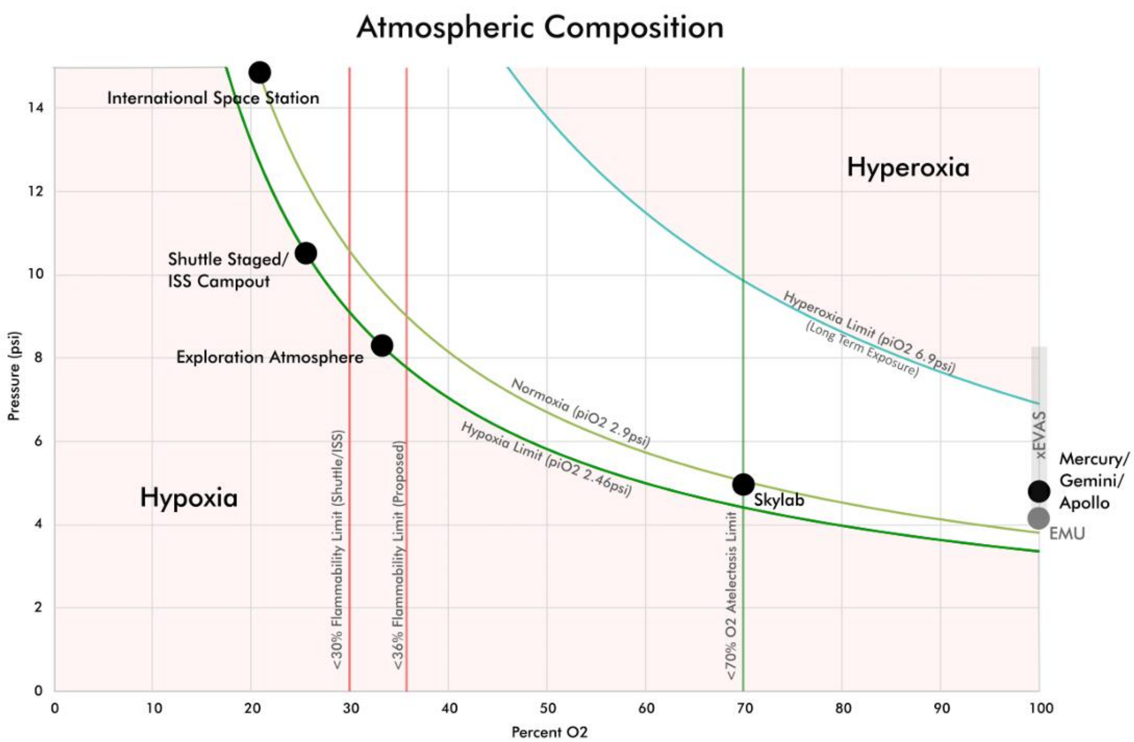


Figure 6.2-1—Atmospheric Composition

Figure 4-2 (Headquarters, NASA-STD-3001 NASA Spaceflight Human System Standard= Volume 2: Human Factors, Habitability, and Environmental Health, 2025, p. 52)

To address the flammability risk, NASA required a buffer gas of 70% for the Space Shuttle and ISS, but going forward looked to lower this to 64%. This would drive the required minimal acceptable pressure to about 500mbar.

NASA looked at this problem as part of a 1975 study that looked into building of large space stations that was consolidated and published in 1977 (Johnson & Holbrow, 1977). In it they proposed an atmospheric pressure of about 500mbar which reduced the stress on each square meter of the structures hull, which permitted a larger structure for a given hull thickness. Based on the newest NASA guidance, this Space Settlement Design Study is at the lower end of what is acceptable and is equivalent to the pressure at an altitude of 5500m.

All recent crewed rockets, including the space shuttle, Dragon Capsules, and the International Space Station operate at 1atm. This is due to a variety of factors including:

- All equipment used and experiments being performed were designed for 1atm
- Air circulation in a micro-g environment is a challenge. A thicker atmosphere circulates better minimizing the potential buildup of a hazardous atmosphere (ie CO2).
- All ships are currently dispatched and returned to earth. Maintaining a constant earth normal pressure makes the transition less stressful.
- Structurally, atmospheric pressure is not a major driver of mass for small vessels. As important as the atmospheric pressure is on structure, the need to lift up the structure from the earth under high g's, the need to protect from micrometeoroids, the need to have a robust structure that will not be easily punctured all add up to determine shell thickness. We will see that for larger structures (hundreds or more meters in size) that are built in space and that don't have to be prefabbed and launched from earth, atmospheric pressure becomes much more important- indeed it is the primary driver in shell thickness.

In short, a 1-atm spacecraft, space station or domed city will have to carry more gas (primarily Nitrogen) and will have greater structural stress, necessitating a thicker shell with greater reinforcement. For this reason, we would want to operate at as low a pressure as possible while maintaining comfort for the colonists.

A compromise pressure would be appropriate for a typical habitat- and I would propose a space nominal pressure standard of 80% of sea level (800mbar)- with some colonies having even lower pressures down to 500mbar. 800 mbar is slightly less than the average pressure in Denver. This would make transitioning to and from earth a little easier for those visiting either geosynchronous orbit, Lagrangian points, or the moon. Having a standard pressure across spacecraft and space stations will facilitate docking and traveling between colonies as well as standardizing design.

Note also that NASA-STD3001 Vol 2 also recommends relative humidity levels to be between 25% and 75% but with a preferred "performance zone" for temperature and humidity that ranges between 30-60% (see Figure 4-3).

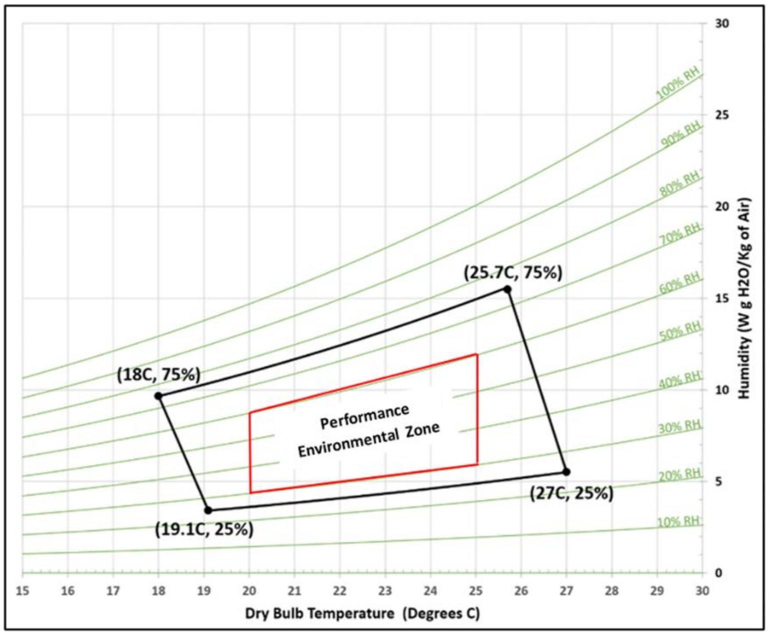


Figure 6.2-3—Crew Performance Environmental Zone

Figure 4-3 (Headquarters, NASA-STD-3001 NASA Spaceflight Human System Standard= Volume 2: Human Factors, Habitability, and Environmental Health, 2025, p. 56)

Protection from Space Temperature Extremes

People also need to be protected from the coldness of space as well as excess heat and radiation from the sun. These are immediate dangers of space as they can kill you within minutes or certainly hours but as opposed to what happens in the movies, the extreme temperatures the astronaut would be exposed to would not kill them in seconds… 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. In space the only way to cool off is through radiative heat, which is a lot less effective than conduction. 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- which is surprisingly hard. 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.

This temperature protection will be provided via a pressurized and insulated vessel and include active heating and cooling. The vessel for a space station, spaceship or colony will most likely be made of a metal shell. If an astronaut is going to conduct a spacewalk, he will be protected by a pressured and insulated suit.

As can be seen from the NASA guidance in Figure 4-3, the recommended relative humidity levels also have recommended temperature ranges from 18C to 27C.

Water

People need water to survive for more than a few days. Water needed for drinking or bathing has, up until now, always been brought up from earth. Early spacecraft did not recycle any water, and it was only with the construction of the International Space Station (ISS) that some recycling was done. As we shall see, water is quite common in the solar system, but it is not evenly spread out. Some objects, like Mercury, Venus, the Moon and many asteroids, have little water. However, others have substantial amounts of water (like the Earth and Mars) and some have a large percentage or even majority as with Europa, Ganymede, Callisto, Titan and many of the comets and asteroids.

The amount of water required will vary depending on duration of the mission and purpose. Current water requirements as published by NASA-STD-3001 are very minimal and are based on the small amount of personnel that have been in space and the limited activity they have been involved in. The standard identifies 2.5L per crewmember per day for hydration, and 400ml for hygiene, and 500ml for Eye irrigation (Headquarters, NASA-STD-3001 NASA Spaceflight Human System Standard= Volume 2: Human Factors, Habitability, and Environmental Health, 2025, p. 68). For long term missions as well as permanent habitates, this will be too low. How quickly and efficiently water is recovered, as well as the uses the water will be put too will ultimately determine the amount of water per person, however it will likely be many times more than the NASA standard.

Food

To date all food has been brought up from earth. As opposed to water on the ISS, food has not been recycled. On earth food ultimately comes from photosynthetic organisms like plants and algae. Above this, we have organisms that eat these organisms for food. In space there is no life so there is no food chain established. Humans will need to cultivate and grow low level organisms via light, water, carbon (from trace CO2 in the spaceships/space stations/colony atmosphere), and minor nutrients. The variety of organisms that will be cultivated will vary depending on the size and needs of the colony, but at a minimum, larger colonies will need to grow various fruits and grains, and likely animals. Fish and the associated plants, as well as selected insects will also be needed.

Power

In space, large sources of power are needed. In many cases electricity, because of its ease of transmission and the fact that it can be converted efficiently into light or mechanical energy and back again, will usually be the preferred form of power.

While power in many ways is not an immediate necessity, it is needed for survival. Power is required to provide heating, cooling, and light, as well as to recycle water, provide light to grow plants for food, excavate and process minerals etc. By almost any measure the creation and consumption of power determines how rich or poor a country is. In Chapter 5 and 6 we will discuss where we can get this power and throughout this book we will explain uses for this power. Some of the largest consumers of power are Propulsion, Lighting, Manufacturing, and Life Support to include Heating and Cooling.

In practice the power demands needed will vary tremendously depending on what it is being used for. Throughout this book we will look at the power needed for propulsion, lighting and manufacturing since these will likely be the largest draw.

Propulsion

For a spaceship, propulsion can be far away the largest consumer of power, whether the power is released over a few minutes by a chemical fueled rocket or months or years if using Ion or electrostatic propulsion. If a rocket uses chemical fuel for propulsion, little power would be needed. On a voyage to Mars using the Methalox engines and not having the requirement to grow food, the crew could probably suffice on only about 1000Watts per person. Conversely, if the ships uses a type of ion or electro propulsive engine, Megawatts of power will be needed. Depending on the efficiency of conversion, up to 90% of the thermal power created could be wasted as heat. Typical nuclear reactors convert about 1/3 of their thermal energy to usable electricity (Chapter 5) and Electric thrusters may be less than 50% efficient in converting electricity to thrust (Chapter 6).

Lighting Requirements

For large space stations that do not have a propulsion requirement, lighting will likely be the largest power requirement especially if growing food. In general, 10,000 lux per m^2 for 12 hours a day would be acceptable for growing most plants- though some plants may require up to 35,000 lux m^2. For other areas including public areas, homes and offices, far lower levels will usually be acceptable- 1,000lux m^2 or lower. On earth, in particularly clear days and at noon, lighting may be as high as 100,000 lux, but this is the maximum, and most times lighting on earth is far lower… an overcast day may only be 1000lux.

For large space stations near Earth, or lunar, Venusian or Mercurian colonies, direct sunlight can be admitted through windows to provide most of the illumination needed. However, for more distant colonies or spaceships, artificial lightning will be needed for most or all of the illumination needs.

Finally, artificial lighting for humans could be lower frequency (yellow range) but plants prefer a broader range, including higher frequency light in blue and ultraviolet.

For a large colony that is self-sufficient in food, large areas will need to be cultivated. Depending on what is being grown or raised will strongly determine the illumination requirements. The Space Settlement Design Study said 100 acres would be required to feed 10,000 colonists (Heppenheimer, 1977, p. 128). While it may be possible to improve on this efficiency with properly selected crops or genetically engineered plants, for simplicity and to get an idea of magnitude, lets stick with this number. This works out to about 404,686 m2, or about 40.5 m2 per person. Assuming an hourly average of 10,000 lux per meter, this works out to about 140W/m2. Therefore each person will require about 5700 watts of power. Lighting for farming may be the biggest demand for power, but all this energy used to grow food will also build up a lot of heat. Some active cooling will be required. For planning purposes lets assume that on average, each person in a self-sufficient colony will consume 10,000 watts of power. If food is not grown then the number will be much less- perhaps only 2000 watts per person.

Manufacturing

Depending on the colony location and purpose, Manufacturing can be a very large consumer of power. Refining metals, mining, and transportation via electromagnetic rails (covered later in this book) will require substantial amounts of power.

Life Support, Heating and Cooling

Heating and cooling are big consumers of power on earth. In space there is the additional challenge that the only way to cool down an object is through radiative heat, which is a lot less effective than conduction. Heating is less likely to be a problem since lighting, as well as the operation of electronics, motors, manufacturing and the respiration of the colonists generate a lot of waste heat that will need to be carried away. The amount of power needed for cooling will depend very specifically on the location of the colony. If heat can be pumped into the ground of an icy planet/moon like Titan, Ceres, or Ganymede, then cooling will be far easier than if a large space station is trying to cool itself the kilometer sized radiating panels.

Gravity

No spacecraft has ever had artificial gravity, but for long term survival in space, gravity is required. Most planets that we would consider for colonizing have gravitational fields much lower than the earth. 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 as to the health effects of lower gravity. Many other moons in our solar system have gravitational fields similar to that of the earth's moon or even less. It is unknown as to what are the minimal levels of gravity that humans, plants and animals need to thrive, but it is likely that it needs to be near earth like for at least some species.

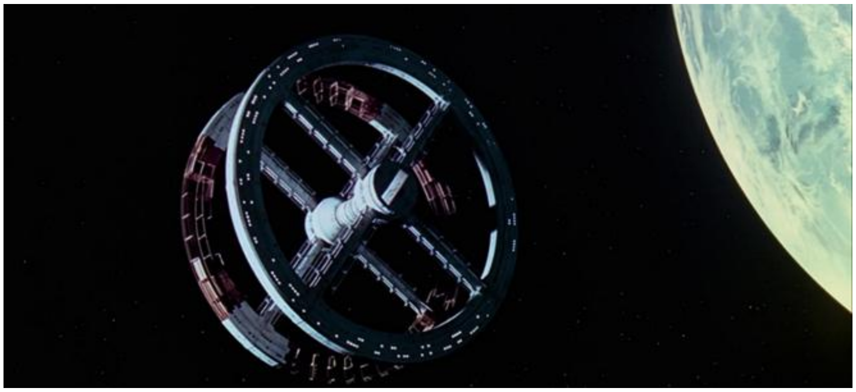


Figure 4-4 A classic rotating space station from 2001: A Space Odyssey

Artificial gravity is easily created via centrifugal force- by spinning an object around central axis. This is why most serious science fiction movies portray large space stations and spacecraft as large rotating torus's, discs, or cylinders. Even though the means to create simulated gravity is rather simple, it is a fairly large engineering challenge. The formula for calculating the gravity of a rotating object is:

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

The lack of planets or moons in our solar system with earthlike gravity has been a strong argument by many as to why we should build large rotating space stations vs large colonies on a planet or moon. In many ways a large space station with 1g of gravity will be much more earthlike than a city on the moon or Mars.

Figure 4-5 The curved Space Station floor from the movie 2001: a space odyssey. note that this space station hull appears to be about 6 meters wide

What are the artificial gravity requirements? What will be the radius?

The size of a space station or spacecraft is primarily driven by the number of people living on it as well as whether there is a requirement for gravity. Artificial gravity drives the 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 real world 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 experience we have is from the Apollo astronauts who spent a few days on the moon in 1/6th gravity. Because of this paucity of data, most studies have drawn uncertain conclusions on what people can tolerate in the long term. From long term Space Station experiments it is known that there are serious effects of zero gravity, some transient and some permanent. In general, the consensus is that people cannot remain healthy in a zero g environment for extended periods of over a year or two. The question still to be answered is for a multigenerational space station or colony, what are the minimal gravity requirements that are required to prevent long-term problems?

An object, being spun around in a cylinder will feel a gravitational acceleration per equation 4-1. 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 4-2 $v = \omega r$

Where $\omega = angular\ velocity\ rad/s$ and is equal to:

EQUATION 4-3 $\omega = \frac{2\pi}{T}$

Where $T = orbital\ period\ measured\ in\ seconds$

Substituting into equation 12-1

EQUATION 4-4 $a_c = \frac{(\omega r)^2}{r} = r(\frac{2\pi}{T})^2$

Substituting into equation 12-2

EQUATION 4-5 $F_c = mr(\frac{2\pi}{T})^2$

Rearranging Equation 12-5 we get the following for r:

EQUATION 4-6 $r = a_c(\frac{T}{2\pi})^2$

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 4-1 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).

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.

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).

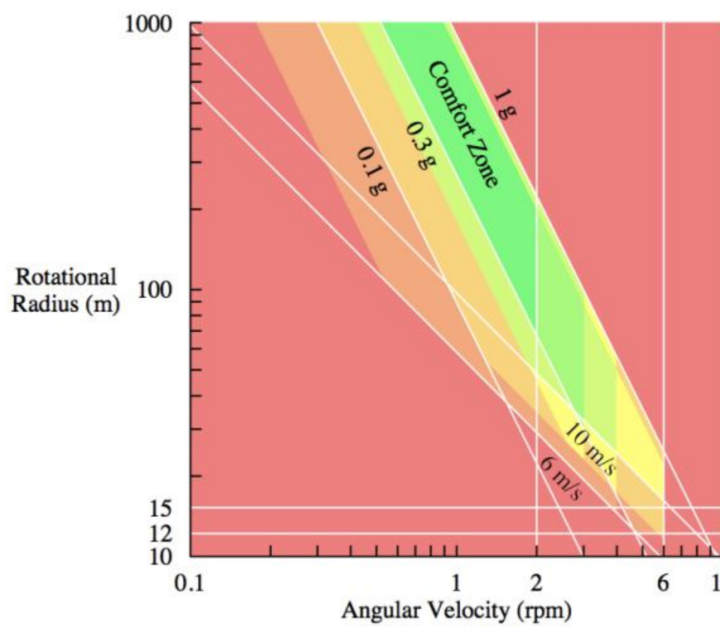


Figure 4-6 (Globus, Space Settlement Population Rotation Tolerance, 2017)

Despite the Settlement Design team's thoughts, most of the literature indicates that people can adapt to a rotation rate faster than 1rpm with no motion sickness experienced. A summation of literature indicates ranges from one to six rpm might be acceptable (**Figure 4-4**). Most studies indicate that 2rpm is probably the highest you would want to go. Nevertheless, the larger space stations with ten's or even hundreds of thousands of colonists will be very large and even lower rotation rates of only 1/2rpm may be preferred.

The radius required to provide near earthlike gravity are significant. The 1975 study addressed many of the same issues had the following parameters for their space station:

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 4-2 Stanford Torus Specifications

One concern that arises when looking at possible colonizing bodies is the fact that most target planets and all of the target moons have gravitational fields far lower than earth's. The long-term health effects of lower gravity are unknown but could be severe. Nevertheless, smaller gravities require much smaller rotational diameters, significantly simplifying construction and reducing mass.

We know long term exposure (6 months or more) to zero (or micro-gravity) have health impacts including loss of bone mass and eye issues. Many symptoms can be partly mitigated by extensive exercise while in space so that most astronauts have little or no lingering effects upon return to earth. However, it is believed that several years in micro-gravity could have severe permanent effects on the astronaut's health both while in space and on their return to earth. Many of the issues, including concerns over reproduction (fertilization and gestation), could perhaps be mitigated by even a low 10-20% earth standard field. Unfortunately, other than a couple of days on the moon, we have no experience with low gravity and do not know its long-term effects and have no idea as to the required gravity to eliminate the worst effects.

I have selected, hopefully conservatively, gravitational parameters for future colonies. In general, I assume that we can go down to .65g with no or extremely minor ill effects. Regardless, Mars and in particular the lunar gravity are very low and concerning from a long-term health perspective. At the very least, long term life on these planets (say ten plus years) will make transitioning back to earth gravity difficult- though the transition from Earth to a lower gravity will likely be fairly easy. Being born on these lower gravity planets may make transitioning to earth gravity impossible. If it turns out that the lunar or Martian gravity are too low for permanent existence, it may be possible to mitigate- perhaps by having people spend a day in a 1g centrifuge once a month or so, but similar questions will need to be answered for all other life we may bring off planet- including plants and animals.

For now, I would propose the following target gravities for various stations and spacecraft and would propose a standard of 1rpm with some exceptions to ½ rpm for selected colonies:

Station	Proposed Artificial Gravity	Comment
L5 Colony	.9g	1 rpm or slower
Earth-Mars Cyclers	.65g	Designed to transition back to Earth or outward toward Mars
Lunar Elevator	.65g	Designed for transition either back to earth or outward towards Mars
Asteroid Rings	.9g	
Jupiter/Saturn Cycler	.65g	Designed to ease transition to lower g Jovian/Saturn moons, or inward bound towards Earth
Venus Cycler	.9g	Venus gravity is close to Earth (90.4%)
Uranus Cycler	.9g	Uranus Gravity is close to Earth (88.6%)

Table 4-3 Suggested Specifications for Space Stations and Cyclers

Cosmic Ray Protection

It was mentioned that people need to be protected from both the cold of space, as well as excess heat from the sun. In addition to this, people need to be protected from damaging cosmic radiation.

Cosmic Radiation is possibly the most difficult challenge to living safely in space since the easiest solution is very massive. 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.

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 lever.

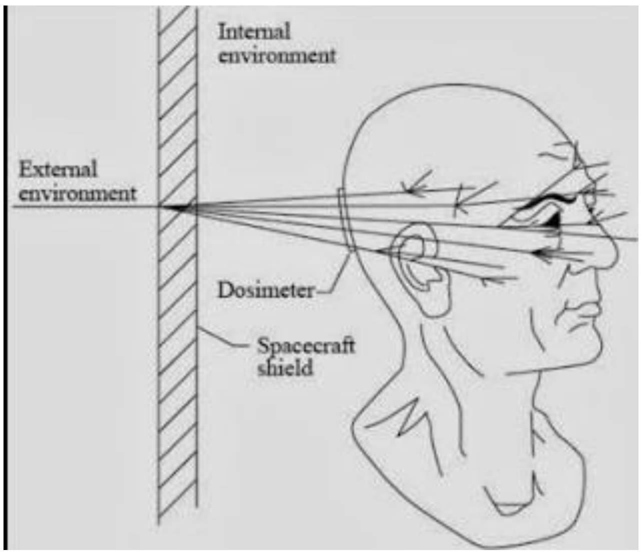


Figure 4-7 cosmic radiation (Courtesy NASA)

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 4-4).

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 Earths 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 a spacecraft and brings a whole host of problems. The Earth's magnetic field is rather week 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 but 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 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 comic 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 nearly twice the tonnage per m^2 to get the equivalent shielding that water and plastic provide. Metals turn out to not to be very good at stopping cosmic rays either. They have the added disadvantage of being very heavy- Water is less than 1/7th the weight of metal per unit of volume. 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 m^2 and at least 6-7 meters thick! This will be a major design feature for a manned spaceship and will add tremendously to the mass of any crewed spacecraft.

	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 Cosmic Radiation Shielding

In NASA-STD-3001 Vol 1 NASA recommendation for missions over 6 months is 20 g/cm2, which converts to a water layer of 200 kg per m2, a much lower quantity than in the Globus analysis. This is likely because NASA is looking at small missions of healthy and highly trained individuals, and not for large and permanent general populations.

While additional studies will need to be made, NASA current limitation for an astronauts career exposure is 600mServ (Headquarters, NASA-STD-3001, Vol 1; NASA Space Flight Human System Standard: Volume 1: Crew Health, 2022, p. 29). a target of <200Rem per year will be used as a reasonable target.

Meteoroid Protection

Finally, we need to address meteoroid protection. Even though it is relatively rare, over time, meteorites will hit our spacecrafts or our colonies. Most meteorite strikes will be of small particles, most no bigger than a speck of dust or grain of sand. However, more rarely, larger marble sized, and larger objects could hit our structures, possibly causing catastrophic damage. Any structure built for long-term will need to be able to handle large and small objects impacting at very high velocities. We will need to consider in our design a wide variety of threats, from the smallest, cosmic rays, to progressively larger cosmic dust, micrometeorites, meteoroid's and ending with comets and asteroids. There is no accepted definition of micrometeorite, meteorite, and asteroid size but in Table 4-5 I break these items up into various categories to represent the spectrum of possible objects that a spacecraft or a space station might encounter. A spacecraft, being restricted by its mass, will only be protected by Category 1-3- but will be able to maneuver around larger threats. A space station will be considerably larger and more massive and not able to be moved. It may be built to last for hundreds of years and will likely have protection, both passive and active.

The passive protection would consist of the spacecraft skin, along with a well known and proven mechanical protection called the Whipple Shield.

Whipple Shield

The meteoroid problem has been looked at before and effective mitigating strategies are available and 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 version is different than the one used on the Japanese module which is different than that used on the European modules.

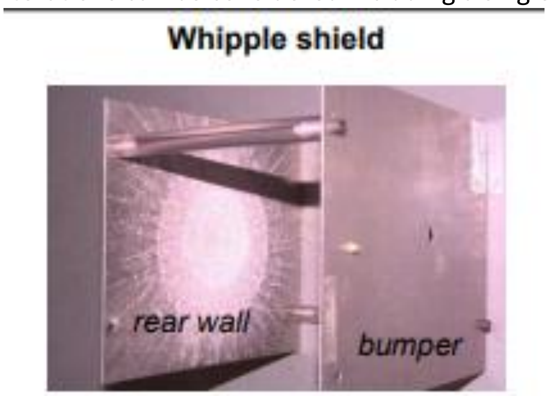


Figure 4-8 Whipple Shield

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.

Various Protection Measures

Besides the Whipple shield, a heavier space station or spacecraft hull thickness can also protect us. Cosmic radiation protection can also serve as meteoroid protection. In Table 4-5 I developed a somewhat artificial category of meteoroids, along with the spectrum of protection measures that can be used.

Category		Size (kg)		Protection
1	Cosmic Rays	Atomic	Atomic Nucleus	Electromagnetic Shielding, Physical Shielding
2	Cosmic Dust, Interplanetary Dust	.001 and below	.01um- 100um (.1mm)	Spacecraft skin, Whipple Shield
3	Micrometeoroid	.001- .1	.1mm-30mm	Spacecraft Skin, Whipple Shield
4	Meteoroid	.1- 999	40mm to 1m	Whipple Shield, Active measures
5	Small Asteroid, Comet	1000kg- 1 million mt	1m- 10m	Large Mass Shield, Active measures, Avoidance
6	Asteroid, Comets, Minor Planets	1 million- 1 billion	10m-99m Undefined orbits	Active Measures, Avoidance
7	Large Asteroids, Comets Minor Planets	1 billion+	100m- 1000km Defined orbits	Avoidance

Table 4-5 Meteroid Protection Measures

The smallest particles that impinge on our spacecraft are the cosmic rays- high energy subatomic particles which we have looked at ways of mitigating these effects previously. I put these in Category 1.

Category 2 are next up in size- Cosmic and interplanetary dust. These particles are so small that normally they would not cause any problems- however their velocities are frequently very high, especially if a spacecraft is traveling through them at 40kps, that they can still cause damage to delicate equipment or erosion damage. A space suit provides enough protection for those doing a short spacewalk, but there may need to be some reinforcement at the front end of the spacecraft where the most particles will be encountered especially if the spacecraft travels for many years. Category 2 objects are swept out over time by the radiation pressure from the sun, but they are constantly renewed as micrometeoroids, meteoroids, asteroids and comets collide. Note that the hull thickness of a small space ship or space station will be about 4mm, but larger structures may be several times thicker. When we design a sample space station, we will calculate some possible structure thicknesses using different materials.

Category 3, Micrometeoroids are more of a problem as they may mass as much as a few grams. The largest particles can easily penetrate a spacesuit. A Whipple shield is usually placed in front of a spacecraft or space station to prevent damage to the underlying structure. All spaceships on prolonged voyages of months or longer, should have some sort of shielding on the forward portion of the ship to protect up to Category 3. The energy of even a 10gram projectile if traveling at 50kps is quiet large:

$$KE = \frac{1}{2}mv^2 = \frac{1}{2}\,(.1)50{,}000^2 = \;250\, million\; joules$$

This is the equivalent of about 60kg of explosives.

Category 4, Meteoroids, are those objects between .03m and 1m and may have velocities perhaps as high as 70kps, and will have huge kinetic energy. Assuming a 100kg mass, and a pretty much worst-case velocity of 70,000mps, we would have to protect against about 490 billion joules- or about 117tons of

TNT. Such a large and powerful impact needs to have a robust Whipple shield, supplemented by some active intercept methods.

For any long-term space station a robust shield needs to be built fully enclosing our structure and for rapidly moving spaceship, a robust (though likely lighter) shield built in front of the ship. Fortunately, as discussed for our cosmic ray protection, a water-ice shield would need to have about 7 tons of shielding per meter- or a shield about 7m thick around any large space station or domed colony. If using compacted regolith, we need around 11-12 tons of mass per meter, or about 4-5m thick. This should be sufficient protection of items up to Category 4. Additionally, we would likely consider some active protection- radar or optical sweeps could pick up larger Category 4 objects out hundreds or thousands of kilometers away. For items on the smaller end of the range, a laser could ablate a portion of the incoming meteor and divert it, or if small enough, vaporize it. Larger items could be diverted or shattered by kinetic energy projectiles- perhaps steel darts impacting at high speeds.

For smaller asteroids in Category 5, cosmic ray shielding may be thick enough to protect from slower moving objects (10-30kps). For larger or faster moving items, kinetic energy weapons will also be effective. Larger Category 5 objects should be picked up tens of thousands of kilometers away giving time for kinetic weapons to shatter the object into smaller, less damaging, pieces. A large Category 5 object if not intercepted, could destroy even the largest space station, or at best, seriously damage any domed city or large moon or planet colony.

Category 6 objects are quite large and will need active defensive measures for the rare but not impossible times that one may approach a space station or spaceship. Optical and radar sweeps as well as extensive surveys should pick up these items millions of kilometers away. Kinetic Energy weapons should be useful to either divert the asteroid, or shatter it. Many of the larger Category 6 objects will have known orbits and will likely be known months or years in advance and be able to be avoided.

Finally, we have Category 7 objects. Most of these have already been identified within the inner solar system. Over the next few decades, various observation satellites, including the Gia Spacecraft, as well as ground-based observatory's, should have identified all 100m and larger objects that orbit within the orbit of Mars. As our observation surveys improve in the coming decades, we will be able to identify similar objects out past Mars, as well as to start developing surveys of objects less than 100m in diameter. These size projectiles are so large that they would destroy any space stations, domed colony and would also cause substantial damage to terraformed planets or the Earth if they impacted.

Due to the high speeds of these objects, they have tremendous energies. There are several models of crater formation on the internet that will give you an indication of both the width and depth of a crater based on assumptions including the specific gravity of the impacting body, the specific gravity of the impacted body, the speed of the impact and the angle. Calculating for KE and using an online calculator (Schmitt, 2004) I have created Table 4-6. This gives you an idea of what kind of shielding we will need as we go through our space infrastructure in the following chapters.

Level	Size (kg)	Volume (m3)	Diameter	Energy (Mega Joules)	TNT	Tons of TNT	Crater Diameter (meters)	Depth	Comments
3	**0.01**	0.000	0.0192	12.50	3	0.00	0.79	0.20	Spacecraft Skin
3	**0.10**	0.000	0.0414	125.00	30	0.03	1.58	0.40	Spacecraft Skin; Whipple Shield
4	**1.00**	0.000	0.0891	1,250.00	299	0.30	3.15	0.79	Spacecraft Skin; Whipple Shield
4	**10**	0.004	0.1920	12,500.00	2,988	2.99	6.29	1.57	Spacecraft Skin; Whipple Shield; Active
4	**100**	0.037	0.4136	125,000.00	29,876	29.88	12.54	3.14	Spacecraft Skin; Whipple Shield; Active
5	**1,000**	0.370	0.8910	1,250,000.00	298,757	298.76	25.03	6.26	Spacecraft Skin; Whipple Shield; Active
5	**10,000**	3.704	1.9196	12,500,000.00	2,987,572	2,987.57	49.93	12.48	Spacecraft Skin; Whipple Shield; Active
6	**100,000**	37.037	4.1357	125,000,000.00	29,875,717	29,875.72	99.66	24.92	Active measures; Avoidance

Table 4-6 Energy and Crater Dimensions for various meteroid sizes traveling at 50000mps

In Chapter 16 we discuss an organization that I called the Tracking Database Group, whose job would be to keep track of natural and manmade objects in the solar system. This group would, after a few decades of collecting data, accumulate orbital data on all objects in Category 6 and 7, and a partial inventory of Category 5 objects.

Developing Standards and Specifications for Human Needs on Colonies and Spacecraft

We have looked at all the requirements that would allow humans to live in space. To provide near earthlike comfort for permanent habitation, we will need gravity, reasonable atmospheric pressure, heating and cooling, lighting and cosmic ray protection similar to that found on the earth. These requirements will drive the need for very large structures. Due to the effort and cost, it would be more efficient and cost effective in the long term to build these structures to last hundreds if not thousands of years. As we proceed on identifying the resources needed to build space ships and space stations, we need to start developing minimal standards to begin our designs. The standards and specifications need to offer guidance for building habitats that are safe and comfortable. In this chapter we have begun to lay out these standards and specifications which we will expand on in further chapters.

To summarize the specifications for future spacecraft and space stations the following chart gives an idea of the range of conditions that need to be provided so that humans can survive and thrive in:

	Ideal	With Adjustments for most of population	Speculative	Comments
Atmospheric Pressure	70%-120%	50-70% (increased oxygen ratio to offset pressure drop)	21-50%. Increased Oxygen to 100% can lower pressure to only 20% of earth but has deleterious effects (see text)	Lower Atmospheric pressure can be offset by increasing Oxygen levels.

Gravity	1.1g-.8g	.3g-.8g	<.3g	Currently these ranges are all speculative
Centrifugal Rate	<.5rpm	1-3rpm	>3rpm	Based on limited observations
Temperature	15-20C	0C-25C	<0C	
Radiation	<200Rem year	200-1000Rem	>1000Rem	
Typical Passive Shielding	7mt water m2 12mt regolith m2			
Active and Passive Shielding	5mt water m2 9 mt regolith m2			
Light Levels Large self sufficient permanent Space ships and smaller transient colonies	10,000 lux pp 1000 lux pp			
Power Requirements - Large Self Sufficient Space ships, small transient colonies	10kw pp 2kw pp			
dV capabilities - Moon, Mars, Ceres, Asteroid Belt Outer planets and moons				Mars ships will also require aerobraking

Table 4-7

Using these parameters we have:

- Settled on a standard atmospheric pressure of 800mbar for most spaceships and space stations with atmospheric composition near earth like. However, in certain situations or circumstances we may consider lower pressures- down to 500mbar with increased oxygen content to about 340mbar. This will make the environment both more pleasant (higher humidity, better sound transmission) while keeping fire risks manageable.
- Artificial gravities for various types of space stations and spaces ships (including cyclers) where the astronauts will live for longer than one or two months. For these long-term residences, we will want a gravity between .5 and .8g. The assumption made is that there are no physiological advantages to having 1g gravity. Less gravity means that for a given rotation rate the space station or space ship can have a smaller radius which means a lighter spacecraft and also less forces on the spaceship will further lighten the structure. However, for general guidelines to provide the most comfort we will rotate at no faster than 2 rpm, and even slower rates of ½ rpm for the largest stations. For habitats where residence time is less than two months, zero gravity will be acceptable.

- We established the need for 7 tons of water shielding or 12 tons of regolith shielding per square meter for stations and spacecraft that are on missions that last longer than a few weeks. Active shielding can reduce this mass, but in general, since we have little experience with constructing active shielding, the amount of protection it offers, while helpful, may only reduce radiation levels by 25%-50%. Nevertheless, active shielding along with passive may permit shielding mass to be reduced to perhaps 4-6 tons per meter. For now, a target radiation of less than 200Rem per year is the goal.
- For large stations, light levels approaching 10,000 lux are needed for at least 12 hours a day to mimic earth like conditions. Locally we may want more light for certain crops but in other areas we can manage with much less so 10,000 Lux is probably suitable for an average. For smaller spaces ships where food is not grown, an average of 1000 lux per m^2 is adequate for calculating power requirements. Rough calculations indicate that for a large self sufficient and permanently inhabited spaceship, about 10,000 watts (10kW) per person will be required. For transiting spacecraft that don't grow their own food, then perhaps 2 kW per person should be adequate.
- Spaceships will require at least the ability to perform dv of 10kps if used to travel to relatively near objects (moon, Mars, Asteroids). Considerably more capable rockets will be required for more distant objects, particularly if they do not have an atmosphere. Atmospheric braking make Mars, Venus and Titan good targets. In some cases inflight refueling may be possible. The most efficient orbits discussed, the Hohmann transfer orbit, means targets further than the moon or Mars will require years or decades to reach. These times can be substantially reduced by large increases in rocket performance. In addition, to substantially reduce travel times of the more distant targets will require dV rocket performance of 20 kps, and will mean the rockets will be on hyperbolic orbits and will leave the solar system if they are not slowed down via aerobraking or additional rocket thrust.

Chapter 5 - Space- History and Economics

Past- the Story Until Now

Many books have been written about the history of space travel and exploration- and 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.

Present- Economics

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

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

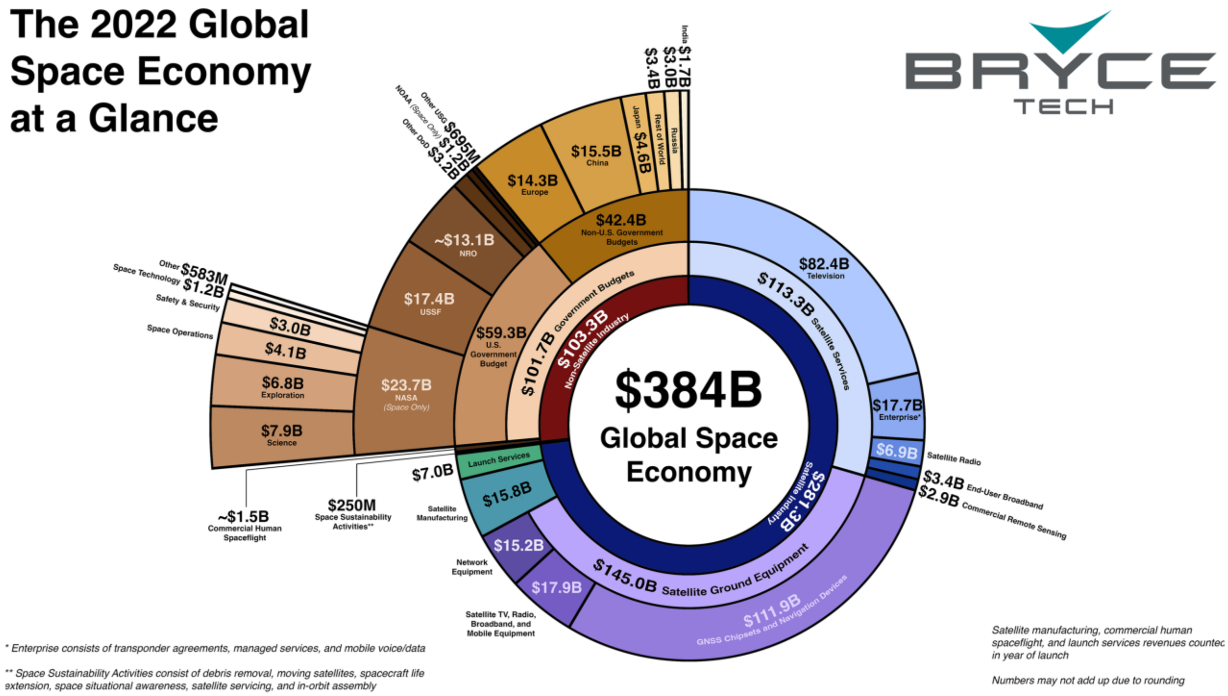


Figure 5-1 2022 Global Space Economy at a Glance (Bryce Tech Publication, 2023)

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 $7 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 with a launch cost of $200 million and have it fail. As a result your satellite is conservatively designed and literally hand built with only tried and true technologies, and because of this a single satellite might cost a billion dollars. The high costs of launch not only ensure launch costs stay high because of a low cadence, but also ensure the high costs of the hand crafted satellites.

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 where the material costs set a floor and as a result price decreases 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. However with satellites we are no where near this point. Many satellites have a similar weight to car or SUV, but cost thousands of times more.

Fortunately, the logjam of high prices for launches has changed- primarily because of 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).

Earth Launch Costs

With current technology and the limits of chemical rocket engines, getting to space is difficult. Using multistage rockets is one way to achieve orbit with a useable payload (see Chapter 7 on the physics of Rocket Engines). The multistage approach, with disposable rocket stages has led to traditionally high costs to orbit. What has been missing until now is a cheap rocket to orbit. SpaceX, first with the Falcon 9, and now with the SpaceX Starship, are rectifying this. Lowering costs to orbit are dependent on four things:

- Reusability. Except for parts of the Space Shuttle, Falcon 9 was the first attempt at making major parts of the spaceship reusable. The first stages of the Falcon 9 are frequently reused over 20x.

With Starship, SpaceX will attempt to make both the first and second stages reuseable. Parts of the Space Shuttle architecture, including the spacecraft, were reuseable, but excessive complexity, reliability problems and low launch cadence negated all of the reusability advantages and by some estimates led to costs approaching $500million per launch.

- Reduction of staging. All rockets have multiple stages to have their payload reach orbit. Most rockets designed in the 50's, 60's and 70's used three stages. Three stages in general makes for more payload with less fuel to orbit- however if switching to a reusable architecture, three stages means that for every launch, three stages must be recovered and refurbished. Beginning with the Falcon 9, most rockets have moved to two stages. Improved technology, including higher thrust, lower weight engines along with the realization that fuel is much cheaper than an additional disposable stage, have made this possible.
- Launch cadence. Until the last ten years, rocket launches were extremely infrequent, a couple of dozen launches per year across the whole globe. Many rocket designs were launched only one or two times a year. Mass production was non-existent. Over the last five years or so this has changed so that hundreds of flights are now launched every year. The Falcon 9 alone launches over one hundred missions a year. High launch cadence, combined with reusability, has lowered launch costs about 75-90% while increasing reliability (see next section). The Falcon 9 launch reliability is over 99%.
- Elimination of centralized government contracts that pay for development. Governments normally assume the costs of most, if not all of the development costs including overruns as the perception was that rockets were still experimental. A better, and much cheaper model is for the government to pay for the service, in this case, a launch service where payment is received when the rocket designer and builder gets the payload to orbit.

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, 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 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).

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 nell for any hopes of colonizing our own solar system.

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 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.

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. Nevertheless, with the recent New Glenn Launches, progress has been made. SpaceX, while also occasionally accepting government money for development work has on the whole, gotten its revenue by 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, 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 substantially streamlined their operations over the last five years. Unfortunately, they have failed to develop a new, revenue generating reuseable 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 meaningful competition to SpaceX with their respective Vulcan and New Glenn. 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 NASAs 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.

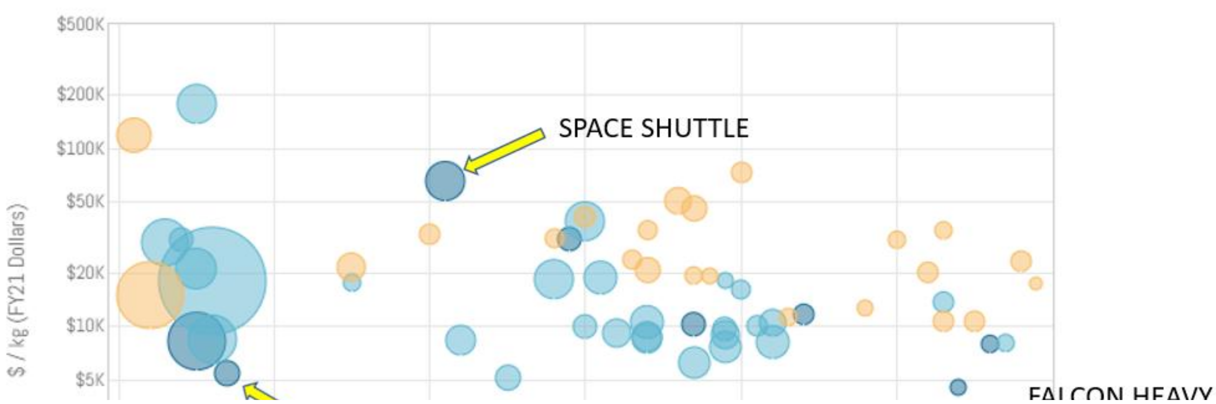


Figure 5-2 Space Launch costs- Annotated with Selected Launchers ***Invalid source specified.***

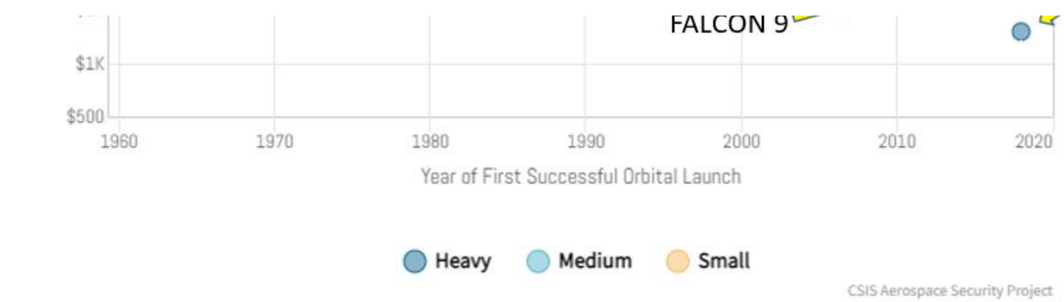


Figure 5-3 Launch Costs

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 $400billion 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 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 very cheap. A robust lunch industry where costs are brought down to $500kg would be excellent, but the lower we can go below this number, the more viable and quickly space colonization will occur. When discussing large beamed Space Based Solar Power (SBSP) in Chapter 12 we will see that this becomes competitive at $100kg, and a preferred source of power at $50kg. I am not convinced launch costs will ever go much below this- in Chapter 7 we will see how for each kilogram put into space we will always need ten to twenty times more fuel by weight. A typical cross country airline flight costs about $5 to $10 kg, and may use about $2kg of fuel per kg of passenger or payload so a rocket launch will need about 10x more fuel/oxidizer per kg than an airline flight, restricting how much cheaper it can be.

What all this means is that, except for the smallest exploratory programs, colonization will need to source most of their raw materials from space.

Current Space Industries- Navigation, Monitoring and Communications

The Current Space Industry is very limited to some specialized markets. Revenue is primarily generated in a few commercial areas:

- Navigation
- Television and Radio relay
- Communications- two way internet or phone
- Weather monitoring
- All other Surveillance and Remote Sensing

Some additional business is done by governments, including science and exploration but most other government business is in the same commercial areas mentioned above. These markets have grown over the last few decades as our technology has improved, but the same basic markets have not changed.

Initially government funded the development and manufacture of launch vehicles which the launch providers also made available to industry. However, in the first fifty years of space launch governments played the biggest role in what was built and launched. This combination of slow cadence, high launch costs and poor reliability make only very profitable markets viable, and as a result, new markets have not developed over the last fifty years.

One of the key takeaways from Figure 5-1 is that most revenue from the space industry is not directly from the satellite or launch vehicle, but it is from the ground services that are sold- the equipment and receivers that are built to transmit and receive the signal from the satellite. The actual “space” portion of the economics is relatively small- with all revenue being paid by the end user. What this means is that the growth of a major portion of the space industry is limited to what the users demand. As such, the demand for navigation, communications, weather reports, resource monitoring will limit the initial space economy to only those things that support Earth needs. As part of this, it will only support LEO operations. This will be able to fund continued improvements in launch services, but not very much will be available to support colonization.

The lower launch costs are permitting new and expanded services. Large communication networks like Starlink and LEO (formerly Blue Origins Project Kuiper) are becoming practical due to improvements in launch cost, launch cadence, and satellite manufacturing costs, along with continued improvements in electronics. This building and launching of these satellites promises to be a major industry for the next few decades but their will be eventual limits to the number of satellites needed. Furthermore, mass production techniques ensure that

Navigation satellites are one of the largest areas of revenue for the space industry- but most of this revenue is associated with the manufacture and sale of ground equipment. These satellites, including GPS (United States), continue to incrementally improve but will not be a source of major growth in space. Instead the revenue is primarily in the ground equipment that picks up the signal.

Monitoring and Surveillance Satellites are also benefiting from these same trends.

While these are robust and real-world industries, they will not directly benefit our colonization program, except that their economic clout will guarantee a modest launch cadence and encourage further development of low cost partially and fully reuseable launchers.

New Space Industry- Tourism

One of the least significant aspects of the current space economy is the Space Tourism industry. This consists of infrequent Dragon capsule launches either into orbit, or occasionally docking with the ISS. Specific costs vary considerably and are difficult to come by. A chart from Statista shows the adjusted prices for an astronaut for various programs based on NASA and the Planetary Society (McCarthy, 2020).

The significance of this industry lies in its the potential. Tourism on Earth is industry is vast and Space Tourism is one of the few untapped potentially huge markets that is funded voluntarily by citizens, in this way bypassing the need for government money. As opposed to the more mature Earth navigation, communications and monitoring industry, this industry is mostly new and may extend beyond Earth orbit.

A tourism industry is also somewhat separated from the whims of government demands as most funding is provided by the tourist. No government contracts required. This insulates it from political pressure and the vagaries of a countries budgeting system. In Chapter 18 we will look at the potential of this industry.

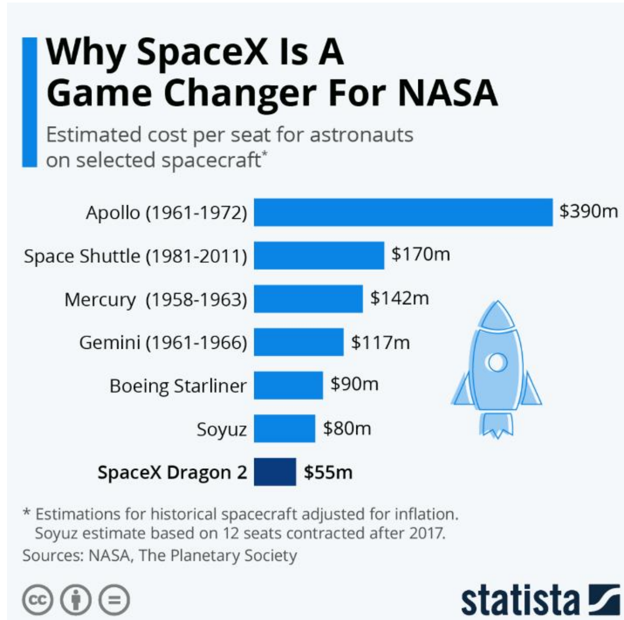


Figure 5-4 Launch Costs per Astronaut

Future Industries that Support Colonization

As we delve into the challenges of Space Colonization, we will see that the demand by governments and individuals will be very low. Funding will frequently only indirectly support colonization by improving launch vehicles, and basic research and development.

There will be a few industries that will directly support colonization, but these are relatively few. Ranked in order of size and likelihood they are:

- Tourism (a large source of future revenue)- Chapter 18.
- A subset of this might be funding by Colonists themselves. People who want to leave earth will not be able to bring their earthly possessions with them. Instead they may pay for a ticket to a colony- similar to when immigrants came to America they had to be paid to be transported. The economics of this are highly speculative and the mechanism needs to be developed but this may be a large source of revenue to pay for equipment and launch vehicles.
- Space Based Solar Power (SBSP)- a possible large source of revenue but highly dependent on public and government support- See Chapter 12.
- Materials manufacture- indeterminate in size but likely very small. The manufacture of large quantities of high value materials that can be manufactured only in low gravity. This potential industry is totally speculative.
- Research and Development of dangerous or polluting industries including genetic engineering and nuclear rockets/power plants.
- Resources- valuable materials can be shipped to Earth but this is unlikely to be practical. One possible exception will be Helium3 mining if this becomes important for Fusion power (see Chapter 6, 12, 19).
- Government sponsored exploration- there will be some demand, likely funded by governments, for the construction of astronomical observatories in space, along with direct field work on planets for geological research

Except for these industries, the Colonization of Space will need to be mostly self-funded. In Chapter 18 we will look at the Space Economy over the next couple of decades and speculate how it might develop.

Chapter 6 - Power for Colonization

Power

A NASA chart (Figure 7-14) neatly summarizes all the options available for a spacecraft (Lyons, et al., 2012). These options apply to colonies, space stations and spaceships.

Chemical energy takes many forms but includes chemical rockets and fuel cells. Fuel cells can provide large amounts of power for short amounts of time, or less power for longer… technically they can last forever as long as you keep supplying the hydrogen and oxygen. They are a good source of abundant power for short (days or weeks) but the need to have large tanks to store the oxygen and hydrogen limit their practicality. Furthermore, rarely will oxygen and hydrogen be available as raw materials. Instead, the oxygen/hydrogen is locked up in water molecules. Separating the two requires a lot of power that would have to come from somewhere. Fuel cells can best be thought of as a type of battery.

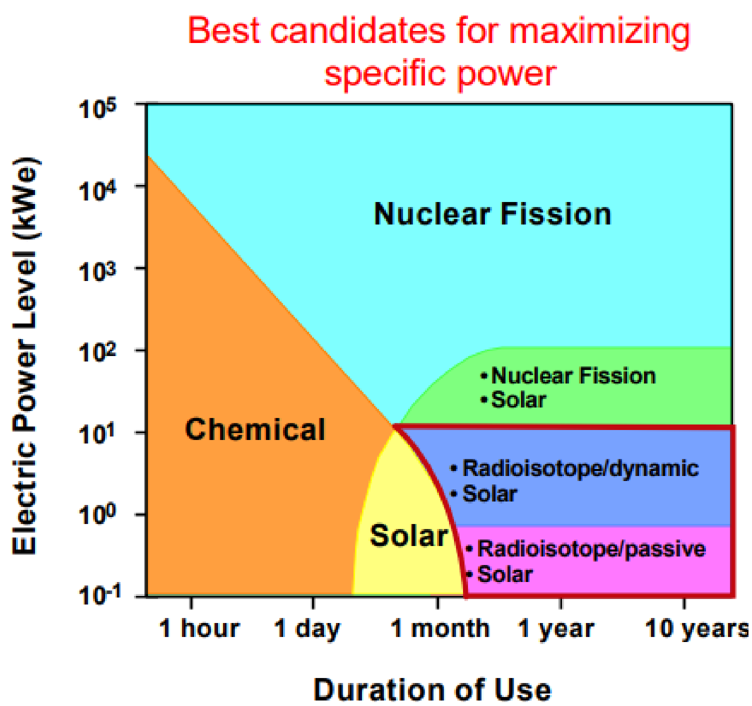


Figure 6-1 NASA Power Candidates for Spacecraft (Lyons, et al., 2012)

Because of the limitations of Chemical solutions, Solar and Nuclear Power in the form of fission reactors will be the primary source of power in space. Further in the future (likely 22nd century) fusion may become available.

There may be isolated cases of alternative power sources for some colonies, but these will be extremely limited. Geothermal, or using the heat energy variation from the surface to deep within a moon or planets surface only works where the body has a large amount of internal heat. This heat is higher on larger bodies, or bodies that are subject to a lot of tidal heating (like Io and Europa). For larger bodies, Mars is probably the smallest body that still has a hot interior and may make Geothermal effective. The Moon and similar sized bodies have warm cores but far cooler than the Earth or Mars meaning that you will have to drill many kilometers down into the crust to get a large enough temperature gradient. Smaller bodies like the asteroids have little internal heating and Geothermal will not be feasible.

Solar Power

Many large stations, including those at Earth Lagrangian points and low earth orbit, will probably use Solar Power instead of nuclear. The early space station, 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 usable 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. At this distance the sunlight intensity is only around 3.4% of Earths. 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. These are cutting edge, expensive and high-tech panels, but we can assume that if mass produced they can be manufactured at a reasonable cost. For our large space stations and ships of the future we will use 35W/kg at 1 au for mass efficiency and reduce this proportionally if we go further out to Mars or the Asteroid belt.

Solar power is indirectly a form of natural fusion power where the reactor (the sun) is unshielded and spews out vast amounts of intense and deadly radiation, but distance, and the protectiveness of the earth's atmosphere and magnetic field, keep it manageable. The biggest advantage to solar power is that the source of power is free… all humans have to do is collect it and convert it into a useable format. The disadvantage of Solar power is that the energy, while vast, is very diluted by its distance. At the earth's distance from the sun a power collector will be exposed to about 1400 watts/m^2. For typical conversion efficiencies of a solar cell of about 25%, this means that only about 350Wm^2 is converted to useable electricity. A large 1 GW_e power plant will require a solar collection area of about 2.86 million m^2- or a square solar array about 1.7km on a side. Ultimately, for distances nearer the sun, solar will likely provide most of the power. The farther an outpost is from the sun the more nuclear power will be used. The transition zone begins at earth's orbital distance and transitions fully to nuclear power out past the orbit of Mars.

While solar power is usually conceived as collecting the sun's radiant energy and converting it to a more flexible and usable form like electricity, we could also directly use the sun's rays for both lighting (including crop growing) and heating.

Solar Power for Earth Orbit and L5 Stations (see Chapter 8)

Space Stations at Earthlike and closer distances from the sun will likely get most if not all of their power from solar energy. Furthermore, the large stations near earth will be permanently inhabited and will be closed systems, requiring small amounts of maintenance supplies but recycling most of their other needs. This means that they will be growing their food. In Chapter 9 we will discuss very large space stations and their design. At many areas, including L4 and L5 spots, solar radiation is constant and never eclipsed by either the Earth or the Moon.

Solar Power on the Moon

Solar radiation is greater on the moon than that on Earth since the moon has no atmosphere to diminish the sun. Furthermore, with no atmosphere, dust accumulation on solar collecting surfaces will be almost nonexistent (as opposed to Mars or the Earth). A significant negative for lunar solar is the long periods of night (over 14 days) at a time which means that no power is available during this time. One way of avoiding this problem is to build a solar power plant at some selected spots at the north or south pole where there exist regions of eternal daylight. These areas are very limited however, severely restricting where a power plant (and colony) can be situated. Because of the long lunar night, solar power is likely to be supplemented by nuclear power, or perhaps fuel cells.

Solar Power on Mars

There are several disadvantages with using solar power on Mars. Because of the Martian distance from the sun, solar intensity averages only 43% of the Earth's, meaning that for the same amount of power you will need over twice the collection area. Furthermore Mars has extensive dust suspended in the atmosphere and during periodic dust storms, can reduce the amount of sunlight getting to the ground by over 90% for weeks at a time. Finally, the large amount of dust in the atmosphere quickly coats all exposed areas including solar panels and unless the panels are cleaned frequently or atmospheric conditions are right (i.e. dust devils remove dust from the panels) panels will need to be swept frequently for dust. Finally, the Mars day is similar to Earth and as a result, Solar will not be able to provide power during the night so will have to be supplemented likely by nuclear power.

Fission

Fission power plants come in several flavors.

Radioisotope Thermoelectric Generator- RTG

The power source most frequently used for deep space spacecraft to date are extremely reliable but low efficiency and low power RTGs. They generate power due to the gradual spontaneous decay of radioactive isotopes that creates heat that can be used for either the direct warming of equipment or the generation of 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.

The most common "fuel" with RTGs 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.

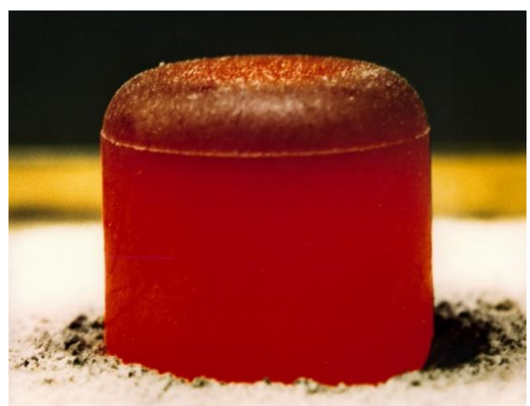


Figure 6-2 Plutonium

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 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 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. For instance, 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.

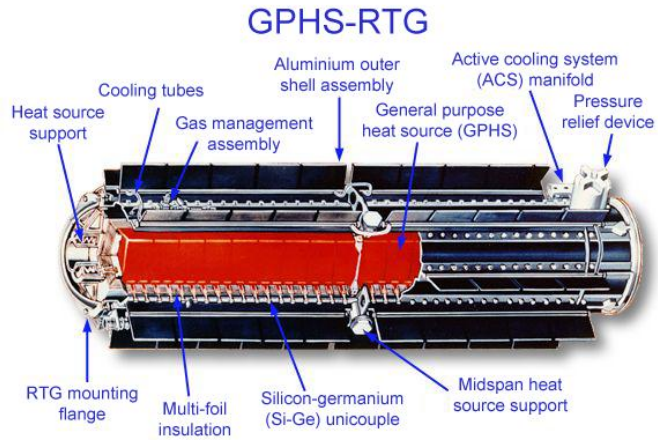


Figure 6-3 GPHS-RTG Cross Section

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 its 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 6-4. 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.

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 be used for a crewed spaceship or colony. The other critical shortcoming with RTGs is there are a limited number of radioactive isotopes that are suitable. Any isotopes used needs to decay rapidly in order to release sufficient heat to generate power which means that they all have relatively short half-lives and therefore there are NO naturally occurring resources available… any of these radioactive materials that may have been available when the earth formed would have decayed long ago. All radioactive materials used for RTGs are manufactured… created for weapons or a byproduct of certain other fission reactions and as such are in small quantitities. Regardless, except for small space probes RTGs are not practical for large scale use.

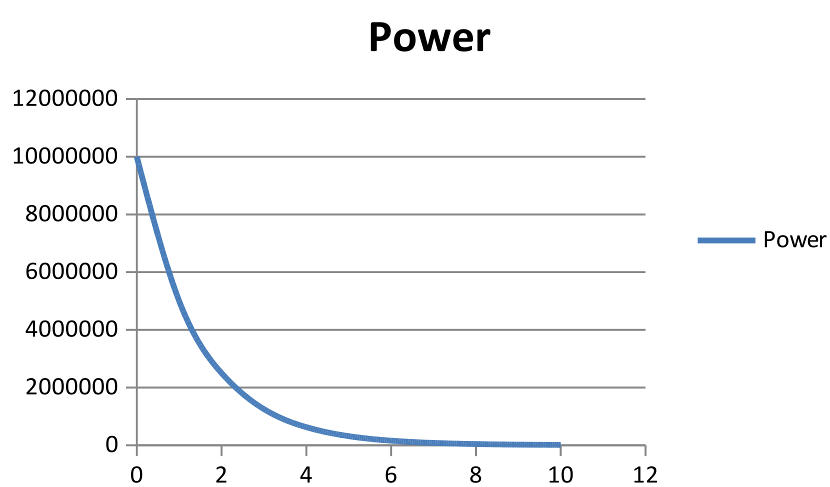


Figure 6-4 Typical power degradation over Half Life Generations

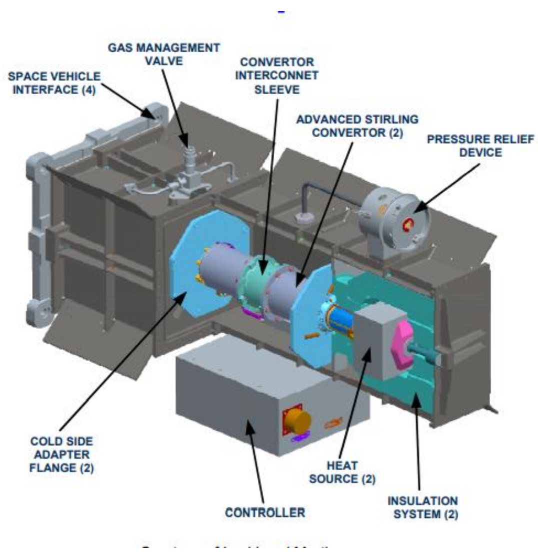


Figure 6-5 Sterling Reactor

Dynamic - Sterling and Reciprocating

One problem with Radioisotope/passive is that they are tremendously inefficient for a given watt of electrical power. There are other types of reactors that are much more efficient. Just above the Radioisotope/ passive portion of Figure 6-1 is the Radioisotope/dynamic. This refers to the Advanced Sterling Radioisotope Engine (ASGR). This generator is a variation of a reciprocating engine and is about 2-4 times more efficient than our baseline RTG per kg of fuel- or about 25% efficient. 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 can 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.

Sterling reactors may have limited use in smaller spacecraft but are not likely to be used for larger colonies and spacecraft mainly because they have the same issue as an RTG in that they need to use manmade radioactive materials for fuel.

Dynamic- Fission Steam Turbine

The next step up in power but needing considerable engineering design work to make flight ready would be a true fission reactor. We have lots of experience with fission reactors, but all of it has been on earth. 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 Sterling Generator (as with KRUSTY) or spin a turbine that would turn a generator to generate electricity.

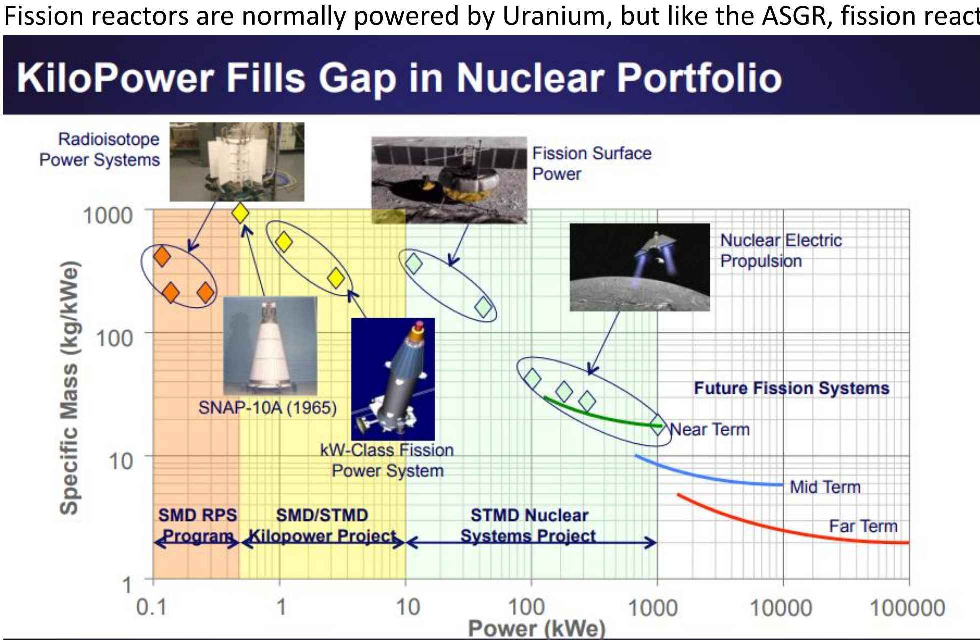


Figure 6-6 KRUSTY- KiloPower Fills the Gap (Courtesy of NASA)

Fission reactors operate very differently from an RTG. RTG power is generated by the spontaneous decay of manmade

Plutonium or Americium which releases heat. Fission reactors also use radioactive decay but 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 natural 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 $1GW_e$ (1 Gigawatt electric).

In Figure 6-6 I show 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. Note that NASA shows a Near Term Future Fission system generating power at 20kg/KWe- or 50W/kg. These numbers seem very optimistic for the Near Term- I believe 20W/kg would be a very reasonable target over the next few decades.

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 704 million years and is present at a concentration of about .72%. ^{238}U is non-fissile which means 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.

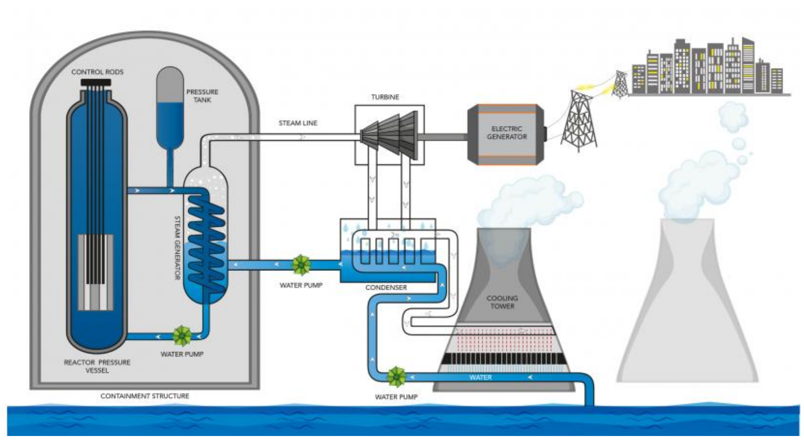


Figure 6-7 Pressurized Light Water Reactor (Office of Nuclear Energy, n.d.)

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.

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 6-6 shows the inverse of this- kg/kWe. On this chart KRUSTY would be about 150kg/kWe.

The KRUSTY program considered designs up to 10kWe of power. Similar to the previously discussed RTGs, KRUSTY incorporated a Stirling engine but instead of using Plutonium or Americium for power, used enriched Uranium as the fuel. In general, as we shall see later, this power size is only suitable for the smallest of spaceships or space stations. Larger spaceships, space stations and colonies will need millions of watts of electricity. While it is likely that the proposed KRUSTY technology can be ramped up, it is unlikely that our larger electricity demands can be met. For this reason it is more likely some sort of turbine powered reactor as is used on earth for nuclear power plants. Their fuel efficiency (watts generated per kg of fuel) is close to that of KRUSTY, and their much larger size may permit some mass efficiencies. Also, turbine reactors on earth are fairly efficient, converting about one third of the reactors thermal energy to electrical power. For planning purposes I will assume that a standardized space reactor of 3 MWt will generate 1 MWe, and using some extrapolation of KRUSTY's 6.67W/kg for mass, up our new standardized nuclear reactor mass efficiency to 20W/kg. From Figure 6.4 this appears very conservative, with NASA projecting future systems able to generate hundreds of watts per kg.

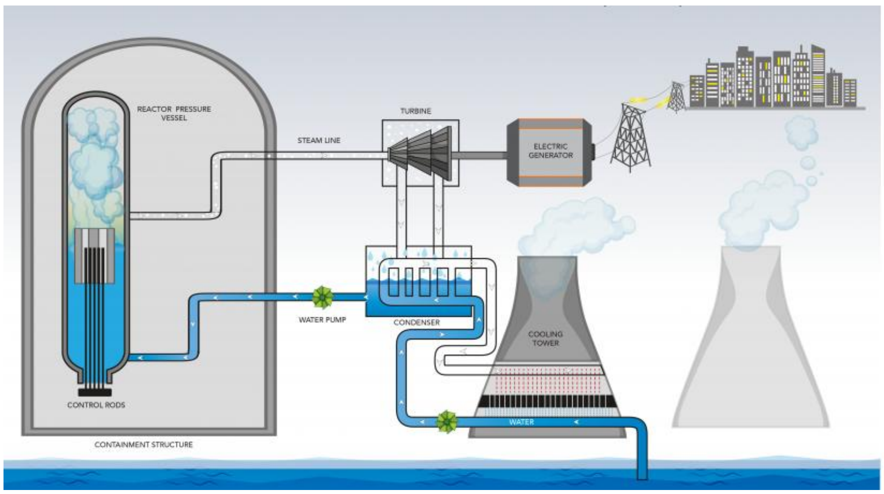


Figure 6-8 Boiling Water Reactor (Office of Nuclear Energy, n.d.)

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.

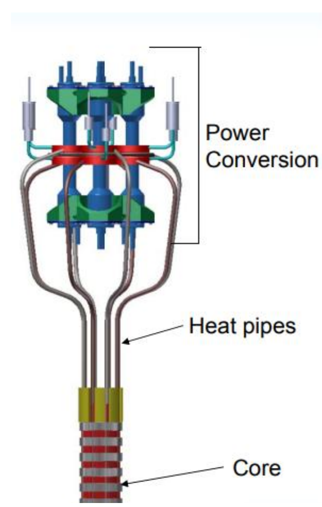


Figure 6-9 KRUSTY- the Power Conversion portion consists of Sterling Generators (Courtesy NASA)

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 replaced with fresh fuel. Reprocessing fuel seems like a no-brainer but on earth (and in the United States in particular) has never been done for political reasons. For space colonies most fuel will likely be reprocessed drastically extending the Uranium supply. 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 colonization, fresh ^{235}U along with reprocessed fuel will be required to refuel our power plants. Reprocessing plants will be one of the first requirements for deep space colonies.

Table 6-1 shows a summary of various current and proposed fission power options.

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	
Radioisotope/Dynamic						Research and Design work done but more needed
Advanced Stirling Radioisotope Engine (ASGR) (Plutonium)	500	135	1.2	32	4.2	
Super ASGR (Plutonium)	5000	1350	12	320	4.2	Enlarged version of ASGR.
Super ASGR (Americium)	5000	1350	41	320	4.2	Enlarged version of ASGR.
Fission						Reactors are common on earth but never built for space
KRUSTY	43.3kW	10 kW	44kg Highly Enriched	1500	6.67	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.
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 that 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	50,000 mt	20	

Table 6-1 Current and Proposed Fission Power Options

Building a representative Fission Reactor- Advanced Space Nuclear (ASN)

In Table 18 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 1 MW_e version of the SSN would, using our rules of thumb that to generate 1MWe for one year we would go through 250kg of fuel. These quantities are small enough that for the initial colonization attempts, fuel can be provided from the Earth.

Another area to look at is to look at what drives our reactor mass? Besides the weight of the nuclear fuel, the containment vessel, the 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 can use the Stefan-Boltzmann Law:

EQUATION 6-1 $\Phi_e = A_i \epsilon \sigma (T_{rad}^4 - T_{sink}^4)$

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 as shown in Figure 2-6.

Suppose we wanted to calculate the surface area required to get rid of 1 MW of power? Rearranging our terms:

EQUATION 6-2 $A_i = \frac{\Phi_e}{\epsilon \sigma (T_{rad}^4 - T_{sink}^4)}$

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_{sink} = 226k (-46C) or the temperature at the distance of Mars. We will assume we are very far out in space.

σ_{sb} is a derived constant = $5.67*10^{-8}$ Wm^2K^4

We will assume a radiator temperature of 150 C (423K). Filling in our equation we would get:

$A_i = \frac{3,000,000}{.9(5.67x10^{-8})(423^4 - 226^4)}$=2000 m^2 or a square about 45 m on a side.

As with many things about designing a power plant and colony, 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 20 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) per Figure 2-6 would be 279K.

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 space station or ship, we may be able to have a relatively low shielding mass.

Thorium

Thorium power generation is very different from your Uranium Fission reactors, but may be a better long term power source since Thorium is 3-4x more naturally abundant than Uranium. Furthermore it burns more thoroughly generating less waste.

Thorium is weakly radioactive- it has a half life of 14billion years. Its long half-life is the primary reason it is much more abundant than Uranium and since its radioactivity is so low, it is relatively easy to handle. Thorium is not fissile- it can't sustain a chain reaction. But the magic is that when it absorbs a neutron it will become ^{233}U which is very radioactive and fissile. The source of the Neutron can be either other ^{233}U breed from a reactor, or ^{235}U. In most designs, the thorium and uranium are at high temperatures where they are in a liquid salt, called a Molten Salt Reactor (MSR) however there are other ways of breeding the 233U including in heavy water reactors and high-temperature gas reactors.

The reaction sequence is:

232Th+n → 233Th+β- (half life ≈22min) → 233Pa +β- (half life ≈27 days)→233U+β-

^{233}U is fissile and puts out slightly more energy per kg than ^{235}U. Once enough ^{233}U is bread it becomes self-sustaining. To initiate the breeding usually 1-5% of the mass would be ^{233}U or ^{235}U, with some additional Uranium added over the first few years. After a few years you will have breed enough ^{233}U built up that you only need to add Thorium to the reactor to keep it self-sustaining. For a large 1GWe facility, you would add only about 1-1.2mt of thorium per year. A major advantage of Thorium over a Uranium fission reactor is that the fission reactor burns a similar amount of Uranium, but eventually you need to remove the spent reactor rods for disposal or very difficult reprocessing. A liquid salt thorium design does the breeding and essentially burns up all the fissile material until mostly short lived radioactive elements remain. As opposed to the tens of thousands of years that a 235U/238U reactor wastes are hazardous, 233U reactor wastes are dangerous for a few hundred years as they don't create Plutonium, Americium, or Curium.

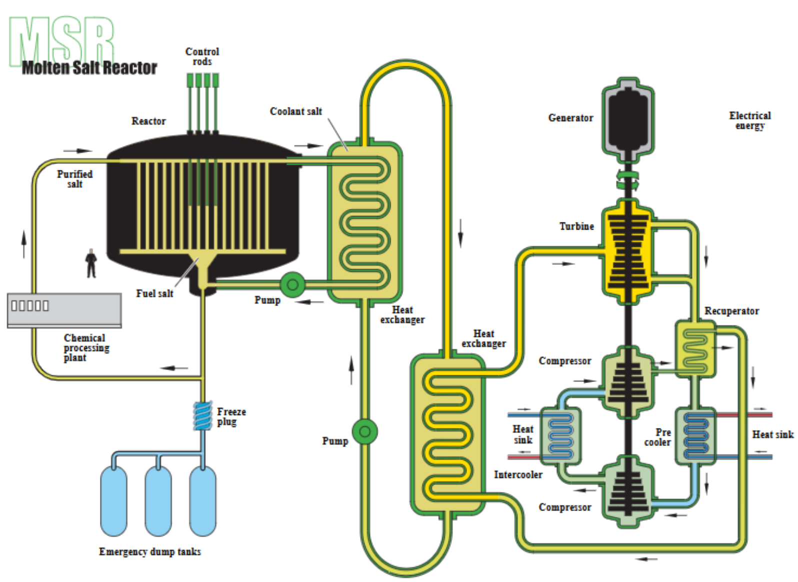


Figure 6-10 Molten Salte Reactor (US Department of Energy Nuclear Research Advisory Committee, n.d.)

The big issue with Thorium is there is far less experience with thorium breeder reactors (though a few have been built) than with traditional reactors so additional design work needs to be done and the infrastructure needs to be built to make a viable earth or space Thorium economy.

An additional limiting factor to using Thorium for space colonization use is that for a given amount of power, a thorium MSR breeder reactor will likely be much more massive than a traditional reactor. On a surface colony or a space station, this should not be an issue, but for a spaceship that needs to keep its mass low, this will limit the thorium MSR reactors use. Thorium MSR reactors have their fuel in a liquid salt, and the power generating ^{233}U is only a small part of this mass, less than 1%. Furthermore they have additional plumbing, pumps, hardware for the breeding system, and some more shielding than a typical reactor.

However, solid fuel reactors can be designed to use ^{233}U as a fuel if the Uranium is removed from the reactor and processed into a solid form. The reactors would need to be designed specifically for ^{233}U, but would operate very similar to a traditional reactor. Gamma Radiation would be somewhat higher as ^{233}U decay produces some small quantities of ^{232}U which is a powerful Gamma Ray admitter, but this can be addressed by some extra shielding and/or physically distancing the inhabited section from the reactor.

Are the more unique elements needed for MSR salts available in the solar system? The elements needed for the salts are Lithium, Beryllium, Fluorine and Zirconium- and all do exist in the Solar System. Beryllium is somewhat rare but can be found in low doses on the moon as well as Silicate Asteroids.

Lithium would be available on Earth, Mars and the moon as well as carbonaceous asteroids. Fluorine is also present on lunar and Martian rocks as well as many asteroids. Zirconium is common in lunar and asteroid silicates. In short:

Lithium: moderately abundant

Beryllium: rare but present

Fluorine: common in minerals

Thorium: more abundant than uranium

Zirconium: very common in silicates

Most of these elements would need to be chemically separated and synthesized to make the salts. In general S-type asteroids and silicate rich bodies (Moon, Mars) would be best to find silicates, thorium, uranium, and zirconium and C-type asteroids for lithium, fluorine, and volatiles. Metallic asteroids (like Psyche) would be very poor in lithophile elements like Th, U, Li, and Be.

^{235}Uranium might initially be needed as a source for neutrons to begin the breeding process but the amount is fairly small. Uranium is in very low concentrations but is widespread throughout the solar system. ^{233}U would be created in the breeding process, or can be taken from a breeder reactor to start up a second reactor (so ^{235}U would not be needed), or can be refined into solid reactor rods and used in a boiling water or pressurized light water reactor that was designed for ^{233}U.

For a large reactor with a couple of percent ^{233}U the actual MSR salt mass would be quite large- a 1 GWe reactor likely will have about 150mt of salt. As can be seen in Figure 6-10 MSR reactors are large and complicated compared to a traditional reactor, meaning they require more maintenance and are more massive watt for watt. With that being said, the larger accessible quantities of thorium over uranium, their more complete fuel burn which contributes to their ability to be refueled periodically with relatively small amounts of fresh Thorium so that they may be able to run continuously, their less long term radioactive waste means that Thorium MSR reactors and the related but more traditional ^{233}U solid fuel reactors will likely be a major source of nuclear power for both the Earth and Space.

Fusion

Fusion, the energy that powers the sun, is the holy grail of energy sources. Fusion reactions are very hard to create and maintain as they essentially need to combine fantastically high temperatures with relatively high densities.

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/m^3 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 and the pressure decreases- over 99% of the sun's fusion occurs within 24% of the suns' radius.

On earth, there are different approaches that are being pursued on the way to creating practical fusion power. In most approaches, the reactors will operate at temperatures higher than the sun but at far lower pressures. One of the challenges with fusion is that to get to the temperatures and pressures required a lot of energy- more than the energy generated. However, over the last decade and with improving technology the "breakeven" point is finally within grasp- if only for a fraction of a second. The next few decades will be concentrated on exceeding the breakeven point and generating power continuously. Eventually practical power plants will be built, but this will likely not be for another 50 years or so. Even when practical plants are built, for the first few decades they will likely be so large as to be unable to be lifted from the Earth. It is likely that, absent some engineering or theoretical breakthrough, we will be well into the 22nd century before compact fusion power plants suitable for rockets and deep space colonies will be available.

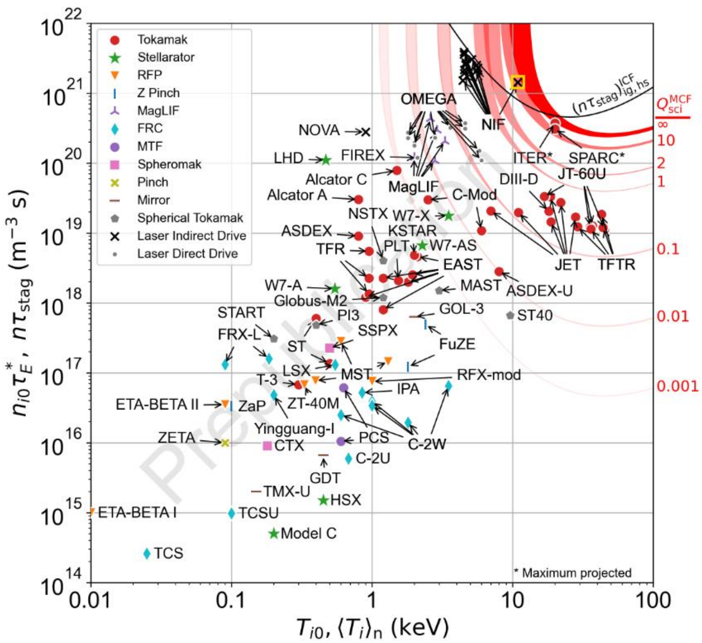


Figure 6-11 Fusion Challenges (Wurzel & Hsu, 2025)

Fusion has the potential for providing large amounts of power even more efficiently than Nuclear Fission. During the fissioning of Uranium, the end product mass is about .1% less than the starting product mass of Uranium. Fusion, for the same amount of mass, converts about .7% of the mass to energy per reaction. Adjusted for the energy released for each reaction, and the differing mass of fission vs fusion fuel, Fusion releases about 4x more energy per kg. Furthermore, as opposed to fission that uses relatively rare Uranium or some other radioactive element, fusion uses the most abundant element in the universe- Hydrogen.

Net power = Efficiency × (Fusion − Radiation loss − Conduction loss)

While progress toward practical fusion has been slow, progress has been real. After nearly 75 years of progress, we are within a decade or two of consistently creating continuous power from fusion. Whether these power plants will be practical enough to provide power for the worlds population, and whether these plants can ever be made small enough to be launched from earth and then provide power for a spacecraft, colony or space station is more challenging and uncertain.

Beamed Power for Colonies and Spaceships

Large space stations will likely generate their own power- whether solar, fission or in the future, fusion. As we saw with Solar, the mass of 35W/kg is probably reasonable for solar powerplants at 1 AU. In the next section we will look at fission reactors but, at least for the next few decades a power mass of 20W/kg looks reasonable. These will lead to massive power plants, but the mass of such power plants is not a big factor compared to the overall mass of a colony city or large space station. However, for interplanetary spaceships the situation is very different since they require the ability to accelerate to high speeds, and less mass means less energy is required for a given velocity.

One alternative way of powering a spacecraft or colony indirectly is by beaming the power. We can generate power in one part of the solar system (either via Solar or Nuclear), and beam it to where it is needed via Microwaves or Laser. In Chapter 3 we discussed the Raleigh Criteria for transmitting electromagnetic radiation. Microwaves can easily be used to transmit large amounts of power (see Chapter 12) but their long wavelength means that the beam will spread rapidly so their range will be measured in tens of thousands of kilometers. For millions of kilometers we could beam laser energy to a receiver which would be collected with solar cells that are optimized for the laser frequency being transmitted. The losses associated with beaming power, as well as the losses associated with converting this radiation back into electricity (either Microwaves or Laser light) mean that the application of beamed energy is likely to be very specialized, but as we shall see in Chapter 6, Electric Thrusters and Ion engines require large quantities of power (many Megawatts or even Gigawatts), and in some circumstances it may be better to generate this power at a large power plant and beam it to a spaceship where it can be used to power its thrusters.

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 a reasonable target that is the 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.

Beamed power provides an alternative to the need to have large nuclear reactors on our spaceship or, if using solar cells for power, can drastically reduce the size and mass of solar panels used as well as extending the range in which solar cells can work. Photovoltaic cells that are tuned to the lasers monochromatic frequency of light can achieve in excess of 50% efficiency (Reim, 2022). A laser beam could have a much higher irradiance, two or more times greater than the sun, further reducing the solar cell collection area (or increasing the power provided) and hence mass of the solar cells per watt generated. Using our state of the art 35w/kg, with an incident radiation being received as 2x greater than normal solar radiation, and if our cells were tuned to the laser frequency we could possibly achieve a conversion efficiency of 50% (twice the more typical 25%), then we might be able to have our power supply provide 140w/kg. This would permit more mass dedicated to equipment/payload or a less massive spacecraft with higher performance. We will look at beamed power for Solar Sail propulsion and for providing large amounts of power for spaceships in Chapter 7.

Large Mirrors (see Chapter 13 (Moon) and Chapter 14 (Mars))

Large mirrors can redirect the sun's radiation to provide either heat or power. In general, these concepts would involve orbiting mirrors hundreds of kilometers across reflecting sunlight to either warm up a region of a planet or to provide sunlight for terraforming schemes.

Space Base Solar Power (SBSP)- Beamed Solar Power (see Chapter 8) for Earth

There are two space-based solutions that can make a meaningful impact to global warming- building large Space Based Solar Power Systems (SBSPs) which will provide greenhouse gas emission free energy, and a Solar Occulus which will serve as a shield to reduce solar radiation and permit a cooler planet. Beamed SBSPS an the Solar Occulus (and the related technology the Solar Mirror) are addressed in Chapter 12 on Earth Terraforming.

Summary and Conclusions

Power is the most precious resource and will be needed in large quantities for both the colonies and spaceships. The local resources and the amount of power needed will be determined by what technology provides the power. The outer solar system (Mars and beyond) will be exclusively nuclear energy.

Chapter 7 - Rockets and Propulsion

The transportation of people is always a challenge. People are relatively delicate and short lived. They need food, air, water, radiation protection and gravity to survive for any length of time. We have seen how travel in the solar system can frequently take several years or even decades. For these reasons, transportation of people will require:

- Relatively high speeds to minimize both the duration of travel and the hazards associated with such travel
- Extensive life support to provide:
    - Air
    - Water
    - Food
    - Radiation Protection (including from Cosmic Rays as well as protection from the Nuclear engines and reactors)
    - Gravity (may not be needed for short trips (<6months).
    - Low Acceleration- likely restricted to 3g for short periods of time (ten or twenty minutes)

For these reasons, the transportation of people will likely have different solutions than those of cargo. Cargo, which we will discuss in Chapter 11, frequently can be shipped in larger but slower moving transporters and usually do not require the delicate handling that people would require.

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 existing from 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.

Chemical Rockets are a mature technology that are near the limits of performance- future improvements will be primarily in reliability and mass.

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 hot air 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 oxygen are mixed and ignited, 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 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 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.

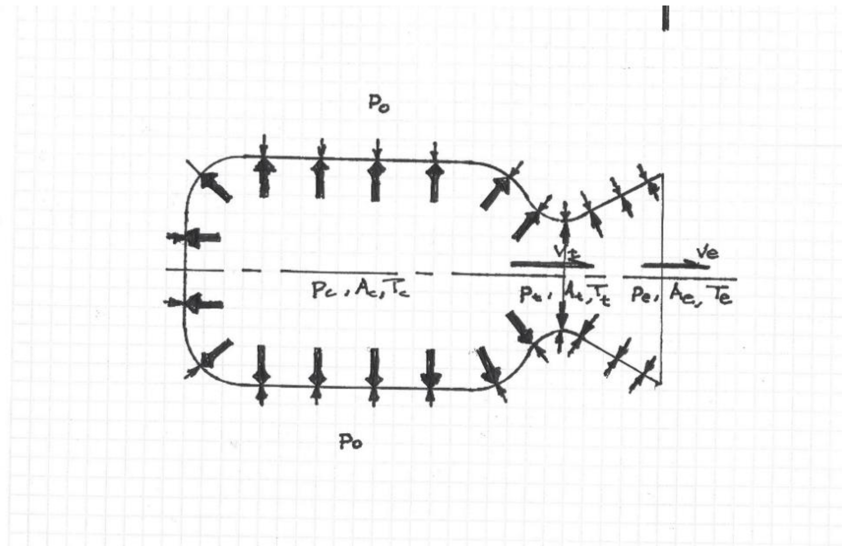


Figure 7-1 The Rocket Engine

The nozzle also does a second important 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 th e 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 7-1 $\boldsymbol{F = \frac{dm}{dt} v_e}$

Where:

$$v_e = exhaust\ velocity$$

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 7-2 $\boldsymbol{F = \dot{m} v_e + (p_e - p_o) A_e}$

Where:

$p_e = pressure\ at\ exhaust$

$p_o = ambient\ atmospheric\ pressure$

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

Rearranging we get

EQUATION 7-3 $\boldsymbol{F = \dot{m}(v_e(\frac{p_e - p_o}{m})A_e)}$

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

EQUATION 7-4 $\boldsymbol{F = \dot{m}v_e}$

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 but 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 rocket equation:

EQUATION 7-5 $\boldsymbol{\Delta V = v_e \ln\left(\frac{m_0}{m_1}\right)}$

Where:

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

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

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

Another variation of this equation is:

EQUATION 7-6 $\boldsymbol{MR = e^{\Delta v/v_e}}$

Tsiolkovsky's work laid many of the mathematical foundations of rocketry but at the time he published them they were not appreciated. In addition to the rocket equation several other concepts that will be important later were 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 7-7 $\boldsymbol{I_{sp} = \frac{F}{\dot{m}}}$

Rearranging this to get thrust:

EQUATION 7-8 $\boldsymbol{F = I_{sp}\dot{m}}$

Additional useful equations are:

EQUATION 7-9 $I_{sp} = \frac{v_e}{g_o}$

EQUATION 7-10 $v_e = g_o I_{sp}$

Where:

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

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

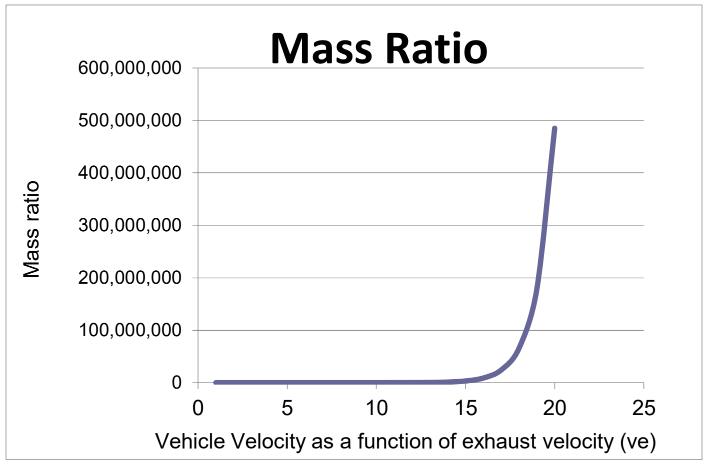


Figure 7-2 Mass Ratio vs Vehicle Final Velocity as a Function of Exhaust Velocity Zero to 20

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.

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 shown on Fig 7-3.

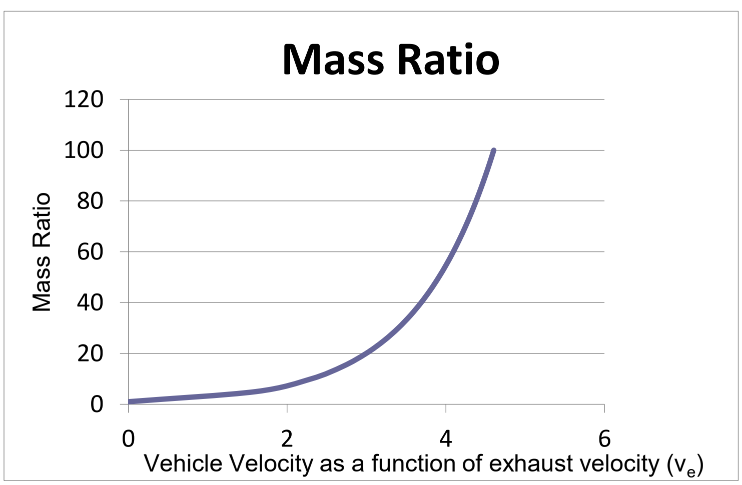


Figure 7-3 Mass Ratio and Vehicle Final Velocity as a Function of Exhaust Velocity From zero to 5

As we 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 us 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.

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. If we desire 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 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. Rockets works by propelling their stored mass in the opposite direction of where you want to travel. 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) or a lighter molecule (the same temperature will accelerate hydrogen much faster than an element of iron) 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. One of the biggest challenges is building materials that can handle the tremendous heat and energy involved with fission engines.

For argument's sake, lets take a rocket with a mass ratio of 20. Furthermore, suppose we wanted to build a rocket that is able to achieve 30 kps. What would exhaust velocity need to be? Using equation 5-5:

Equation 7-11 $\Delta V = v_e l\,n\left(\frac{m_0}{m_1}\right)$

And rearranging the terms we come up with:

Equation 7-12 $v_e = \Delta V/(\ln\left(\frac{m_o}{m_1}\right))$

$$v_e = \frac{30000}{\ln(20)}$$

$$v_e = 10{,}000 mps$$

This works out to an specific impulse of about 1,000. Chemical fuels such as those used by the SpaceX Starship, Space Shuttle and Saturn V rocket, have V_e speeds on the order of 300-450 seconds, or 3000-4500 mps (3-4.5 kps).

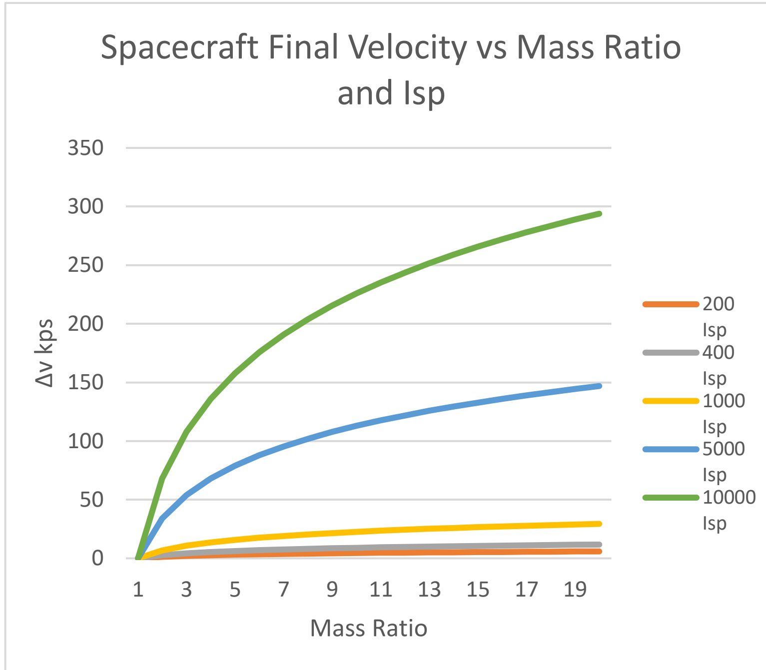


Figure 7-4 Δv vs Mass Ratio With Different Specific Impulse

Another useful version of this equation allows us to calculate the initial spaceship mass. By rearranging the terms we get:

Equation 7-13 $m_1 = m_f e^{\Delta v / v_e}$

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:

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

In the case of the V_e of 10,000 mps considered above, this is on the order of 2.5x faster than a typical chemical engine of 4000 mps. Because of the equation for Kinetic Energy, the power required to generate this velocity would be 2.5^2 or 6.25 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 because they have a very low mass flow.

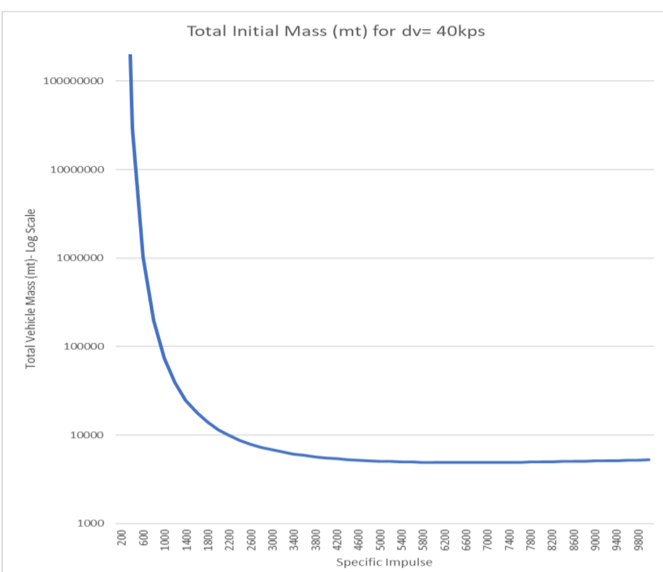


Figure 7-5

In this chapter we are looking at "traditional" rockets, both chemical and nuclear that get their propulsion from the heating of a fuel via either chemical reaction or nuclear. These rockets provide large amounts of thrust and release a large amount of power over short periods of time.

Traditional rockets are the primary means of traveling through space but additional sources of thrust have been developed and occasionally used. The most common alternative is the electric thrusters , including ion engines. These are quite common but because of their low thrust (frequently in micro-newtons) and their high-power requirements, they are usually restricted to station keeping of satellites. Related to these are the proposed mass drivers, where mass reaction is accelerated in magnetically propelled buckets. Both electric thrusters and mass drivers need substantial electrical power to provide high thrust.

Finally, it should be obvious but that the mass flow of the rocket (fuel plus oxidizer) is related to the Force of the rocket and the velocity of the exhaust with the relationship:

Equation 7-14 $\dot{m} = \frac{F}{v_e}$

This equation shows us a very important fact- mass flow will increase as the exhaust velocity decreases if the engine provides the same force.

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

As humans expand out from the Earth, we will encounter alien atmospheres like Mars or Titan that will present some of the same challenges as those on Earth.

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 7-6) and you encounter less atmospheric drag.

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) (Figure 7-7). The force of drag can be calculated by the following equation:

EQUATION 7-15 $F_D = \frac{1}{2}\rho\mu^2 C_D A$

$\rho = mass\ density\ of\ fluid$

$\mu = flow\ velocity\ relative\ to\ object$

$A = reference\ Area$

$C_D = the\ drag\ coefficient - a\ dimensionless\ number\ particular\ to\ the\ object$

Even though the Drag Coefficient C_D is different for different shaped objects its overall profile is similar. Figure 7-8 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.

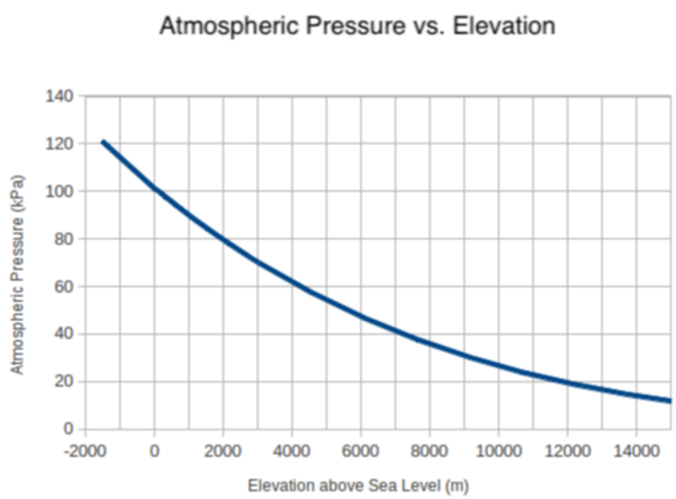


Figure 7-6 Atmospheric Pressure with Altitude

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 ρ and a high C_D will increase your drag.

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 lever. 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.

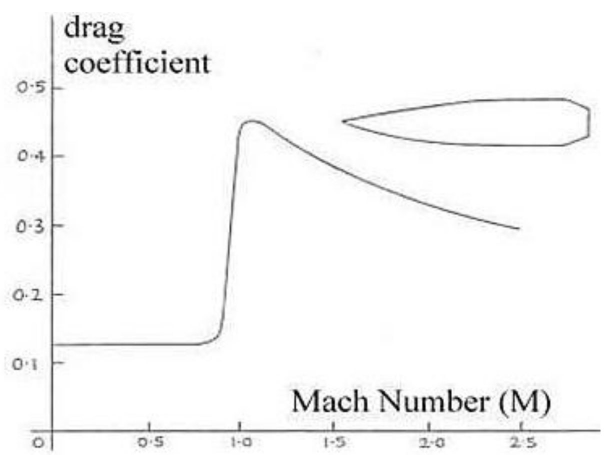


Figure 7-7 Drag vs Mach Number

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 $\frac{1}{2}\boldsymbol{\rho\mu^2}$ is also called dynamic pressure and is referred to as Q. During the ascent of the rocket as $\boldsymbol{\mu^2}$ 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 orbital speed 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.

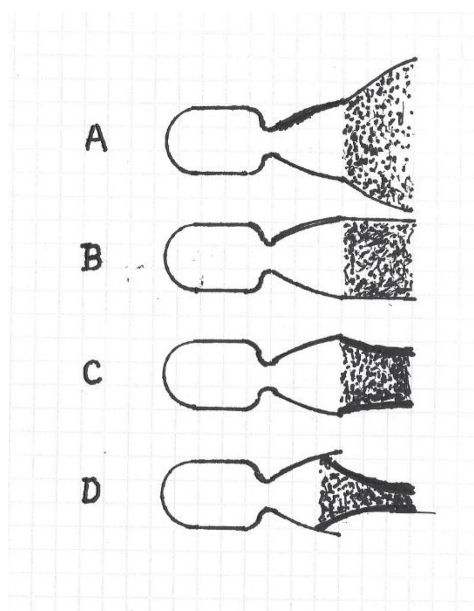


Figure 7-8 Rocket Nozzle

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

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.

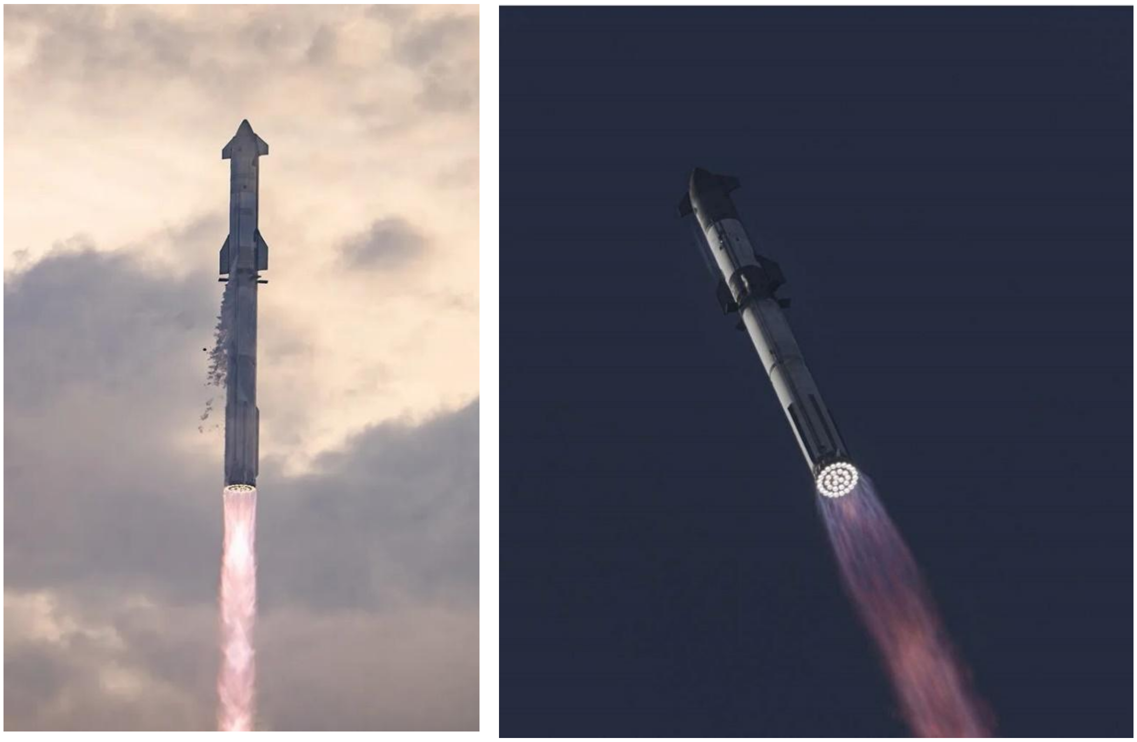


FIGURE 7-9 STARSHIP AT SEA-LEVEL (LEFT) AND AT ALTITUDE. NOTE THE EXHAUST PLUME IS NARROW AT SEA LEVEL, INDEED IT NECKS DOWN A BIT, INDICATING OVEREXPANDED EXHAUST. AS THE STARSHIP GAINS ALTITUDE THE PRESSURE DECREASES AND THE EXHAUST STARTS SPREADING OUT- THE EXHAUST IS NOW UNDEREXPANDED.

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:

Equation 7-16 $$I_{sp} = \frac{v_e}{g_o}$$

Below in Table 3-1 are some of the more popular and common rocket engines with their $I_{sp's}$:

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

Figure 7-10 Various Propellants and Their Specific Impulse (Isp) 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 7-2, 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 rocket's 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 RTG'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. Kinetic Energy follows the Equation:

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

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?

$$K_e = \frac{1}{2}(150{,}000)1000^2 = 7.5x10^{10}\,Joules$$

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

$$K_e = \frac{1}{2}(150{,}000)10000^2 = 7.5x10^{12}\,Joules$$

Or 100x times more energy. This performance is sufficient to accomplish most interplanetary missions but is insignificant to the needs of an interstellar rocket. The distance between stars is so vast that even a 10kps is far to 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 7-17 $P = \frac{E}{t}$

$$P = \frac{7.5x10^{12}}{60} = 1.25x\ 10^{11} watts/sec$$

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

$$P = \frac{7.5x10^{12}}{(24x60x60)} = 8.685x10^{7}\ watts/sec$$

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! We will need far more power. If we are propelling our rocket with chemical engines, and assume our 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.

Types of Rockets

Chemical Rockets

Chemical rockets are the original and most developed type of rocket. They can provide tremendous thrust able to lift the rocket, fuel tank and payload off the launch pad and accelerate them into orbit. The initial chemical rockets were solid fuel- burning black powder or equivalent in a tube or pipe. They were extremely limited in performance because of their low exhaust velocities. Liquid fuel rocket engines have a much greater performance but are also much more complicated, requiring high pressure pumps to transfer fuel and oxidizer into a specially designed chamber where the mixture is burned. Figure 7-1 shows a typical cross section of a rocket combustion chamber and nozzle, with the relevant forces displayed.

Liquid fuel chemical rockets are limited in their specific impulse to about 450. To go higher we would need to either increase the temperature in the combustion chamber (hence the pressure) or decrease the average atomic weight of the exhaust, or both. Since chemical rockets are limited in energy to that of the chemical bonds that are formed, the temperature is limited to the burning of that particular fuel/oxidizer combination. Ideally the burned product would have a very light weight like Hydrogen, however this is not possible as all chemical reactions are between a fuel and (usually) oxygen so that the best case the exhaust product is steam, with the atomic weight of water (18). Other common fuels, like Kerosene or Methane have exhaust products that are heavier. In a Methane/Oxygen engine, the exhaust is water (18) and CO2 (atomic mass of 44) which means that for a given temperature, the exhaust velocity will be slower (though the mass flow- hence thrust- will be somewhat higher). The highest performance rockets that are in common use are the Hydrogen and Oxygen engines (Hydrolox) because they burn energetically and eject the relatively light water molecule. Other fuel oxygen mixtures use carbon compounds like Methane or Kerosene.

Nuclear Thermal

Nuclear- these proposed rockets come in three flavors. In Nuclear Thermal Solid- a fuel (usually hydrogen) is heated via nuclear rods and escape via a nozzle as with a chemical engine. Nuclear rockets usually run cooler than chemical rockets but have higher performance due to the low atomic weight of the hydrogen. Furthermore, there are theoretical nuclear engines, called liquid and gaseous types that promise extremely high exhaust velocities. These have no major theoretical obstacles, but the engineering challenges are formidable.

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.

The advantage of the Nuclear Rocket was that it had a large Specific Impulse compared to traditional chemical rockets- about twice as high (if using Hydrogen for fuel). Note that Nuclear Thermal does not get its higher performance from higher temperatures than a chemical rocket… indeed they generally 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 us hydrogen for a fuel (actually H2) which has a much lower atomic mass than the water released in a LOX/LH engine- with an atomic weight of 18.

From NERVA to Project Timberwind, it was believed that specific impulse could be raised from about 850 to 1000 seconds- but this may come at the expense of engine durability. Furthermore, the nuclear thermal engines being developed were quite small and compact- in one case the engine being only 1500 kg. 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, that also would be designed for durability and infrequent fuel swap outs. This engine would have the following specifications:

Isp= 900

Engine mass=3000kg

Thrust= 1150 kN

Flow rate=130 kg/s

In general, this engine would double the performance of an equivalent Hydrolox spaceship. In the case of a spaceship with an empty mass of 150mt and a total mass of 3000mt we will have a substatntial interplanetary spaceship. With the specified flow rate, and our a 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. Most of the tested Nuclear Engines were only good for perhaps an hour of operation before the fuel needed to be replaced. Changing fuel after every hour, or after any mission, is difficult, time consuming and not economically efficient- and will require substantial quantities of nuclear material. Nuclear fuel can become much more competitive if durability is improved and the engines are designed for changeouts only after many missions. Designing an engine that could last a dozen or more missions should be feasible with further research. Engines limits are primarily driven by wear and tear of operating temperatures near their limits and the aggressiveness of hydrogen on the reactor materials. Durations can be vastly expanded by reducing the reactor temperatures but this will reduce the Isp. Current technology limits their exhaust temperature to about 2750k, above which they will start to melt.

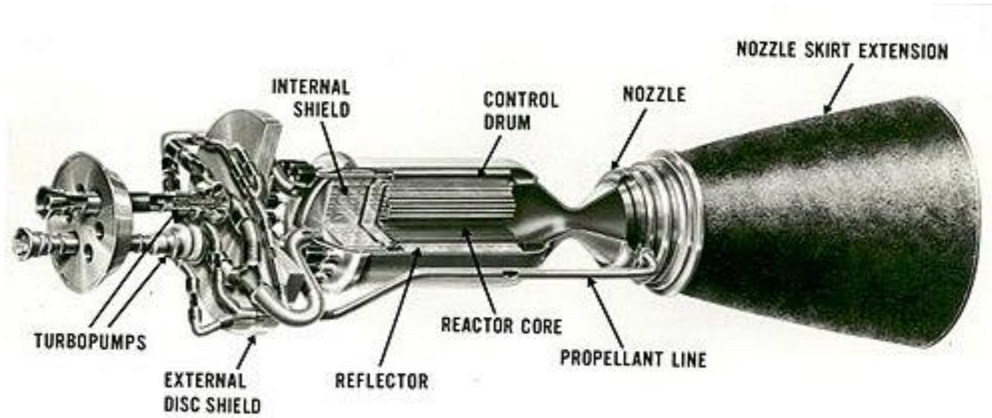


Figure 7-11 Nuclear Thermal Cross Section (Courtesy of NASA)

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 a viable option for an interplanetary spaceship. 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.

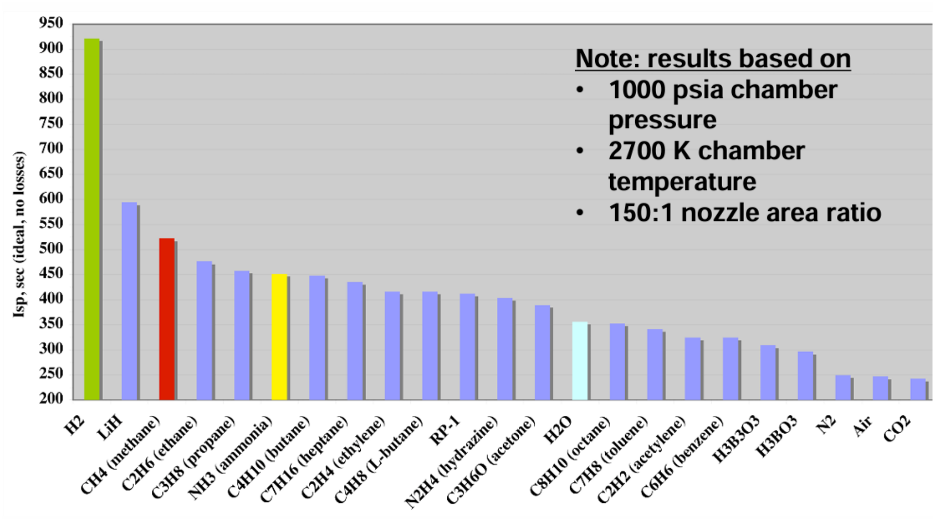


Figure 7-12 Representative Isp's for different fuel (NASA , 2019)

Nuclear thermal engines are feasible to land on certain bodies, including the moon, Asteroids and Mars as their exhaust is not radioactive (unless the engine is damaged or starts melting down). Nuclear thermal can be used for launching from the Earth but because of the risk of radioactive release in a crash or damaged engine, may not be politically feasible. Furthermore their thrust is adequate for Earth lift off but is usually about half to a third of an equivalent chemical engine thrust (mainly because of Nuclear engines use the light hydrogen molecule for reaction mass) requiring either more engines, less payload, or a variation of both. The SSME generated about 1840kN of thrust and massed about 3.2mt, as compared to the improved 3mt Phoebus engine. However if carrying people, the Nuclear Thermal rocket will need appropriate shielding, because while the exhaust is not radioactive, the engine while running IS. Shielding the engine from the passengers further increases the engine mass and further limits payload making an Earth launch spaceship dubious. I can see Nuclear Thermal engines for both high velocity manned spaceships that are not used to land on Earth as well as large cargo ships used for the movement of cargo's at slower velocities throughout the solar system.

Electric Thrusters and Ion Engines

Human cargo is in a hurry. Humans need food, oxygen, heat etc. A leisurely mission is both inconvenient and dangerous as humans will be exposed to elevated cosmic radiation for the duration of the trip. Cargo transportation can frequently be more leisurely and hence require lower thrust and dV. Cargo, especially raw materials, will likely be much more massive than the spaceships used for personnel transport. Because of this, Cargo and raw material transportation will require the movement of more mass but at lower velocities. Low thrust but highly efficient rockets are likely to be the propulsion of choice.

The performance of electric thrusters are extremely high- they are very “mass” efficient for the fuel they use. However, they require large amounts of power which means that their acceleration is slower and their final speed is reduced. Furthermore, increasing the electric thrusters exit thrust requires more power and hence a heavier powerplant. This leads to the need to optimize- depending on the watts per kg of your power plant and the Isp of your engine, there is an optimum power plant mass. All things being equal, as you Isp goes up, the power would scale to the square power. Assume that we have a two spacecraft that have the ability to perform a dV of 20 and 40kps respectively. Let us also assume both produce a thrust of 1,000 nt and an m_0 of 1000 metric tons- but excluding the power supply mass. Assume that our power supply (whether the Super Space Nuclear from Chapter 4 or from solar panels) is able to generate $20W_e$ per kg of power plant mass. If we use our equations, we get the following curves:

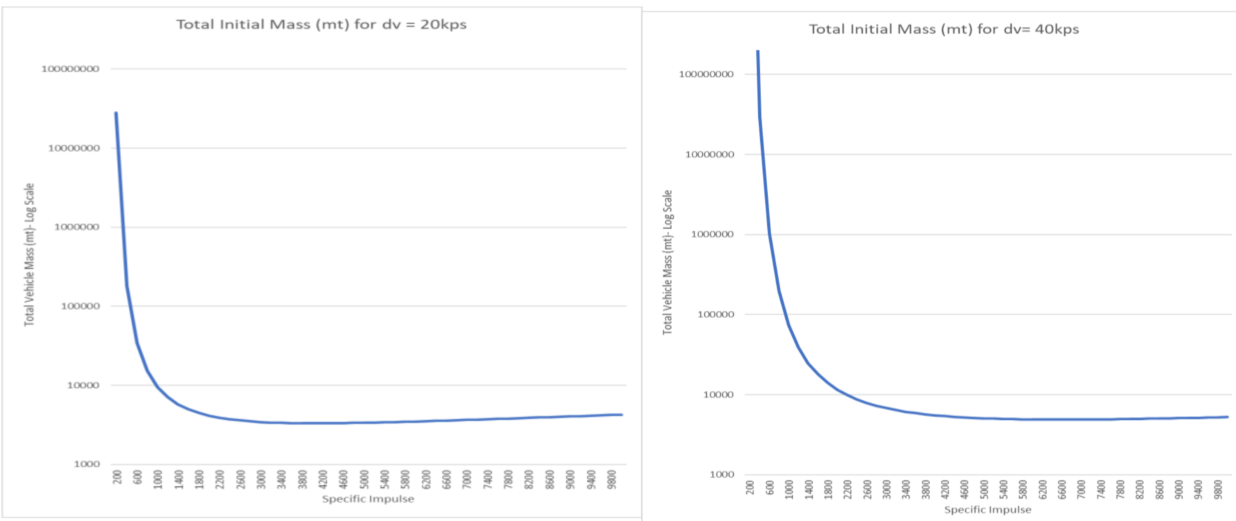


Figure 7-13 Powerplant Mass as it affects Performance

It is hard to see because of the scale of the large mass ratio’s required for a very low Isp, but these curves illustrate several important points. For any particular dv, a higher Isp will require a larger power plant, even as the mass flow is reduced to keep the thrust constant. In the above graphs, the spaceship with a target of 20kps has the minimum mass occuring at an Isp of 4000 seconds. An Isp higher than this means that the increase efficiency of mass expelled is offset by the mass of a larger power supply. If we have a spaceship whose performance is increased even further, to a target dv of 40kps, we will have the most efficient mass occur at an Isp of about 6600.

We saw in Chapter 5 how chemical rockets and nuclear thermal rockets are limited in the specific impulse that they can provide. However there are certain types of engines that can provide specific impulses of several thousand to ten thousand- called Electric/Ion thrusters.

There are a variety of Electric Thrusters and Ion engines. They operate by accelerating ions across a high voltage grid. The ions provide the thrust. Electric Thrusters are usually very mass efficient with extremely high specific impulses, but are extremely low thrust. Thrust can be improved but only at the expense of requiring more power. Ideally, an electric thruster could go to the stars, but the power requirements are extremely large. Electric thrusters have proven very reliable, frequently operating for years. They are usually used for small station keeping adjustments for Earth orbiting satellites but a few have been used on interplanetary missions that required large dVs- most famously for the Dawn spacecraft that visited the Asteroids Vesta and Ceres.

There are two basic versions of electric propulsion- plasma and the Electrostatic or Ion engine of which Ion Engines are the most common. Both types come in several flavors- they can use different fuels, and generate and accelerate plasma in different ways. Typically electric thrusters have specific impulses 10-20x higher than a chemical rocket. They are also known to be reliable and have been in widespread use for over 50years.

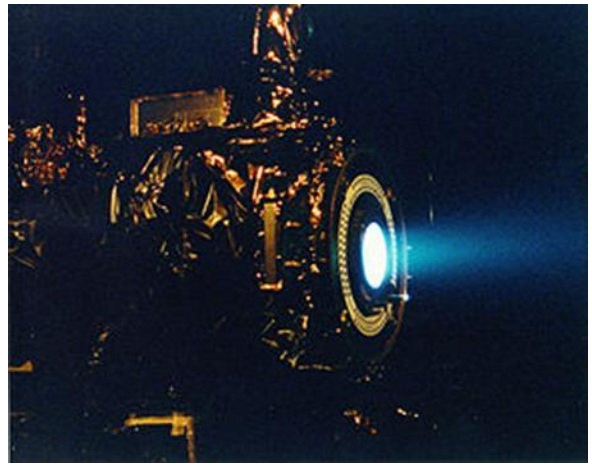


Figure 7-14

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, FEEP, 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 7-18 $I_{sp} = \frac{v}{g} = \sqrt{\frac{2qV}{m}}$

Were:

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.

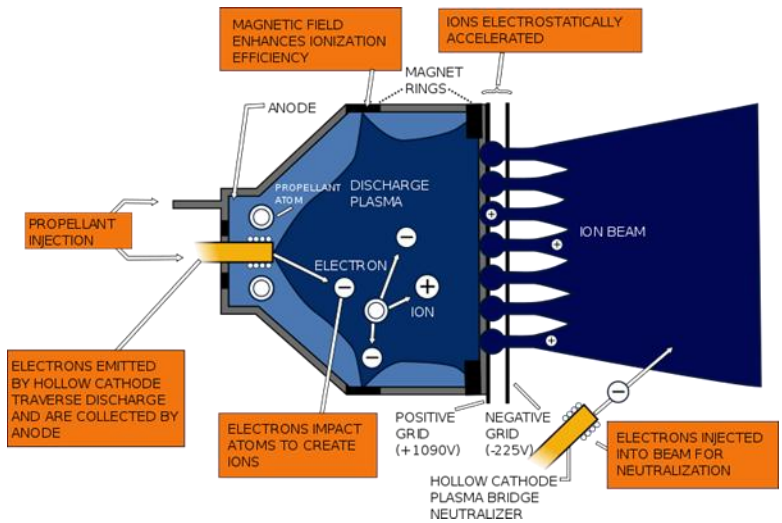


Figure 7-15

Ion engines can use any atom as a reaction mass. 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 relatively high. However other factors turn out to be more important- including the fact that the material should be liquid or gas so they can be stored and then pumped to the motor when needed. Noble gases are not reactive, and therefore will not explode or react with other materials. Furthermore, 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 Krypton or Xenon.

An additional factor when selecting the reaction mass material can be seen in Equation 7-1, that lighter atoms will give the highest Specific Impulse since, in a given magnetic field they will accelerate the fastest. Conversely the heaviest atoms will give the greatest thrust but a lower Isp. By the criteria of specific impulse, hydrogen or helium are the best materials, but both are hard to handle. Both require very low temperatures to become liquid (helium needs to be down to around 4k, hydrogen around 20k) and even then these liquids are not very dense requiring large, and insulated, storage tanks. Hydrogen has an added challenge of being extremely reactive so will cause a lot of wear on the electric grids. Helium has the challenge of being very difficult to ionize.

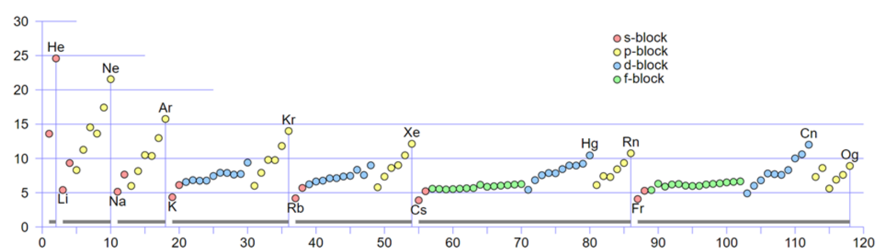


Figure 7-16 ***Ionization Energies for Various Elements***

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, along with their performance are:

	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 **Hall AEPS**	1000-5000 2600	40-600mN 1770mN	1.35-10 kW 40kWe **56kWe**	 68.7	Xenon; In Use- station keeping for satellites Xenon
HiPEP	9600	670 mN	40 kWe	7.11	Xenon. Demonstrated at 40kW. Project was cancelled in 2003
MPDT (Choueiri, 2009) (Glenn Research Center)	1500-6000 10000	2.5-25N 100N	100-500 kw **6.25 MWe**	? 1000	Hydrogen, Lithium, Ar, Xe .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 7-1 Performance Comparison of Electric Thrusters

Electric engines are at the simplest level, engines that take electric power and convert it to thrust. Their performance is partly influenced by their efficiency- often around 50% or lower. But the physics is the same. If you double your thrust, yon either need to double your input power or half your exhaust. For a particular engine you can describe the electric engine with the equation:

Equation 7-19 $F = \frac{2nP_{in}}{v_e}$

Where n= efficiency.

This equation shows us that force is dependent on both Power In, the efficiency, and the ve. When we also use the equation:

$$\dot{m} = \frac{F}{v_e}$$

We can graph the relationship between thrust and Isp. If we take a hypothetical Ion engine and show that for a constant force and a fixed efficiency the electric engine will have the curve shown in Figure 7-17.

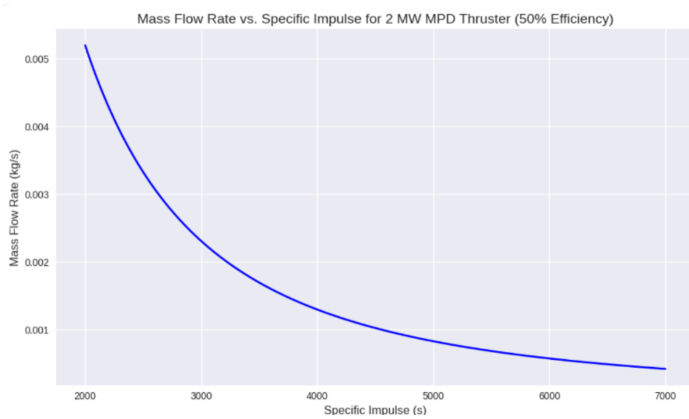


Figure 7-17 Relationship of Mass Flow with Specific Impulse

Possible future improvements for Electric Thrusters electrostatic engines that use metals for fuel. The metal is vaporized, ionized, and accelerated out the back just as with the current ion engines. The advantages are that fuel storage is simplified (a block of metal) and the higher atomic weights of many metals will lead to higher thrust. Some negatives are that for the same power you will get a smaller specific impulse, and now you need energy to vaporize the metal which requires more power. How capable these engines are is unknown, and the laws of physics dictate that you will always require tremendous power for high thrust and impulse, but metal ion engines are an area that provides an alternative to traditional ion engines using noble gases.

Electric Thrusters and Ion engines and low thrust have prevented them from becoming the preferred method for propulsion when traveling in the solar system. However, with enough power you can keep scaling up their thrust. The VASIMR and MPDT in Table 7-1 thrusters can provide several newtons of thrust. The speculative MPDT version can provide 100nt of thrust for about 6.25 MWe. Electric thrusters and Ion engines are not 100% efficient in the conversion of electric power to thurst. As noted in Chapter 4, Nuclear power plants are about 33% efficient- a 3 MW_t (thermal) reactor will generate about 1 MW_e (electricity). Now we need to factor in the efficiency of an electric/ion engine, which, depending on the exact design, the reaction mass used etc. will range from 30-70% efficiency. Assuming a 50% thruster efficiency, our 3MWt power plant will generate only 500kW that is used for thrust- and the remaining 2.5MW will be waste heat.

It is likely that multi-megawatt power plants will be constructed and operated in space over the next 100years. A large earth reactor may generate 1GWe, or 1000MWe. We can imagine a 1GWe plant providing 20,000N thrust through an electric thruster. A 1 GWe power plant would mass about 50,000 mt (see Chapter 4 on a fission plant) so a 20,000N thrust engine would accelerate at .0004 mps^2, if the whole rocket were a power plant. If we assume the total spacecraft is twice this mass then our acceleration of .0004 mps2 will provide us dv of 17.3mps after one day of thrust. This is leisurely but big enough that we can work with for deep space, multiyear missions.

The options to improve performance is to either increase our thrust by more adding more power, or reducing the mass of our reactor by increasing the watts generated per kg of reactor mass, or by reducing our specific impulse.

Currently, Argon is the least used of the noble gases for satellites. This is because of its relatively high ionization energies and the fact that its lower mass atom means higher exhaust velocity but lower thrust- and for most cases, the higher thrust is desired. As a larger space-based industry is developed the preference for using Xenon and Krypton may change. Both of these are rare in the earths atmosphere and as a result are much more expensive than Argo to recover (Table 7-2) from the atmosphere.

	PPM in the atmosphere	Total Atmospheric Mass in kg	Cost per Liter
Argon	9340	$4.8x10^{16}$	$0.50-$1.00
Krypton	1.14ppm	$5.854x10^{12}$	$3500
Xenon	.087ppm	$4.471x10^{11}$	$1200-$1500

Table 7-2

Argon is a major component of the atmosphere (about 1%) and therefore relatively easy to distill and costs on the order of only $.50-$1.00 per liter. A space based industry that uses 10,000 mt of Argon per year would have a 4.80 billion year supply so it would unlikely be a resource concern. Conversely Krypton would last 587,600 years and Xenon about 44,700 years- while still a sizeable amount, a large space based demand might raise future resource concerns. It is for these reason that I can see Argon as becoming more popular than Krypton or Xenon for Electric thruster applications.

Electric thrusters/Ion engines have tremendous potential for station keeping, or moving large payloads over many years. They are not very effective at getting people or cargo moving very quickly. As such, their usage will be limited unless paired with a high energy chemical rocket (see Chapter 8).

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.

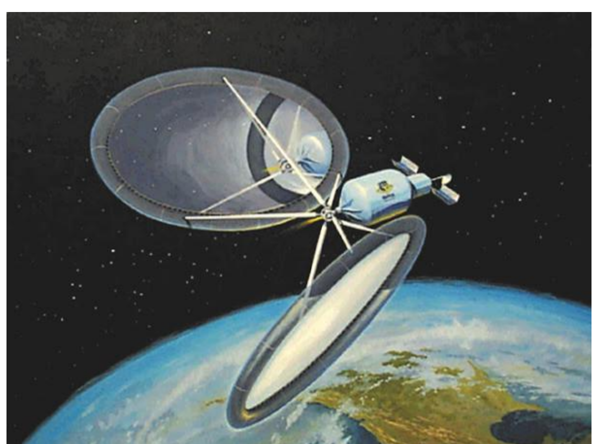


Figure 7-18 Solar Thermal Rocket

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.

Nuclear Fusion

Fusion as discussed in Chapter 4 can be a source of power. But it can also be a direct source propulsion.

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 He_3 is extremely rare. When considering this challenge, the easiest source for He_3 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 (Sviatsolavsky, 1993).

Because of these factors, I don’t think fusion research will be a key requirement for interplanetary spaceships or large space stations in this century. However, I will talk about the longer term potential of fusion in Chapter 17.

Fusion Rocket

In many ways, the ultimate dream for interplanetary spaceship 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 Sails

Solar sails are a dream technology as they eliminate the need for fuel. A solar sail uses the radiation pressure from the sun (or a laser) to provide the propulsive force. Unfortunately for the solar sail, light pressure is extremely small and a solar sail needs to be both very large (frequently many square kilometers in size) but lightweight to provide any significant performance. Solar sails are to a great extent reliant on material development similar to that required for Space Elevators.

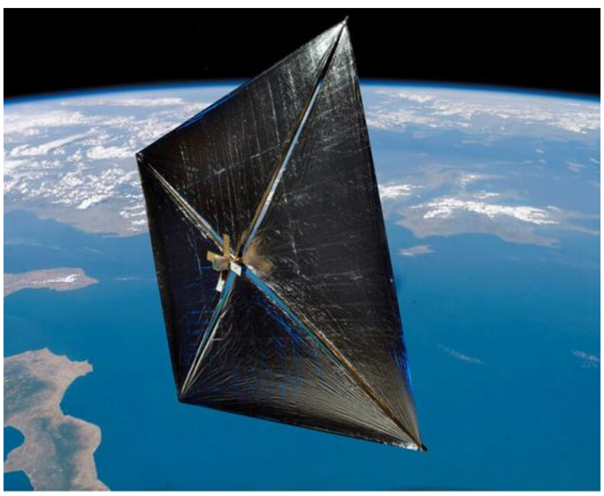


Figure 7-19 Solar Sail in Earth Orbit (Courtesy of NASA)

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?

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 7-20 $F_{Light} = \frac{I}{c}$

Where c is the speed of light in mps and I is the light intensity per m^2 or about 1366 W/m^2.

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. With Solar sailing the situation is a bit better than a 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 7-21 $F_{Sail} = \frac{(1+k)I}{c}$

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 m^2

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 7-22 $A_{Circle} = \pi r^2$

$$A_{Circle} = \pi(6{,}371{,}000{,}000)^2 = 127{,}516{,}1177{,}977{,}447m^2$$

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.

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 7-23 $F = ma$

Rearranging

EQUATION 7-24 $a = \frac{F}{m} = \frac{5}{150{,}000{,}000} = 3.33x10^{-8}$

If we wanted to get up to the substantial speed of 10kps we would take:

EQUATION 7-25 $v = at$

EQUATION 7-26 $t = \frac{v}{a}$

$$t = \frac{10{,}000}{3.33x10^{-5}} = 3x10^{11}sec = 9{,}500\ years$$

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 but his assumes the larger sail is no more massive than the original 800 m^2 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:

Equation 7-27 $\sigma = \frac{m}{A}$

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 100m^2, then our sail loading would be 1000g/m^2.

A typical material used, mylar, weighs about 7g/m^2. With our example square solar sail that was 1.6km per side, with and area 2,560,000 m^2, if we used mylar the sail would weigh 17920 kg.

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.

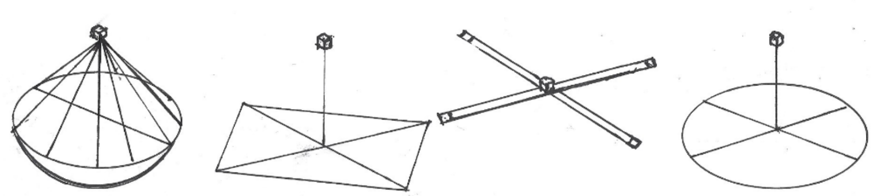


Figure 7-20 Types of Solar Sails – Parachute; Square Rigid Sail; Heliogyro; Spinning disk

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 a an 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.

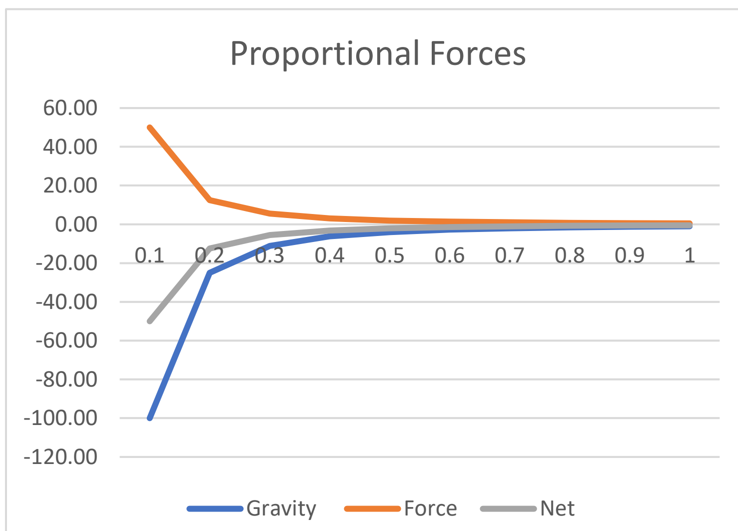


Figure 7-21 Gravity vs Solar Sail Forces vs AU From Sun

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 suns' 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 $1.82x10^{-5}$. The sun's gravity at the earths distance is $5.93x10^{-3}mps^2$. Solving for mass:

$$m = \frac{F}{a} = \frac{1.82x10^{-5}}{5.93x10^{-3}} = 3.069x10^{-3}\frac{kg}{m^2} = .003069\frac{kg}{m^2} = 3.069\frac{g}{m^2}$$

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.

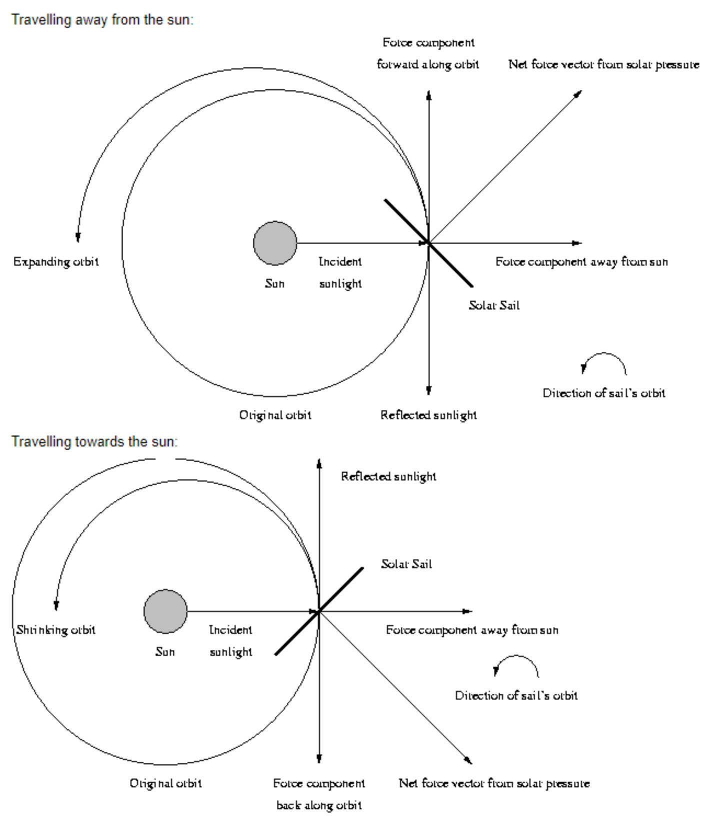


Figure 7-22

Let's go back to our first case where we proposed a 1.6km square solar sail with an area of 2,560,000 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.

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 $1/38^{th}$ – 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 $meter^2$ and the suns acceleration at the earths distance is $5.93x10^{-3}mps^2$. Solving for m:

$$m = \frac{F}{a} = \frac{9.1x10^{-6}}{5.93x10^{-3}}$$

$$m = 1.53x10^{-3}kg/m^2 = 1.53g/m^2$$

Or, as we would expect, half the mass we calculated 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/m^2 or about $1/10^{th}$ 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 $1.38g/m^2$. Again, if 50% of the mass were payload, the sail would need to be only .69 g/m^2- 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, and continuously accelerate.

Using a sail loading of .765 g/m^2 our 150,000 kg sail will now have twice the area of our second case. We will now have a sail $1.961 \times 10^8 m^2$ 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 7-28 $v_{esc} = \frac{42.1\lambda^{\frac{1}{2}}}{r^{\frac{1}{2}}}$

Where:

EQUATION 7-29 $\lambda = .001574\frac{\mu}{\sigma}$

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, μ=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 μ=.9. If we assume that manufacturing capabilities exist to make a spacecraft with a sail loading of ½ that of gravity then we have:

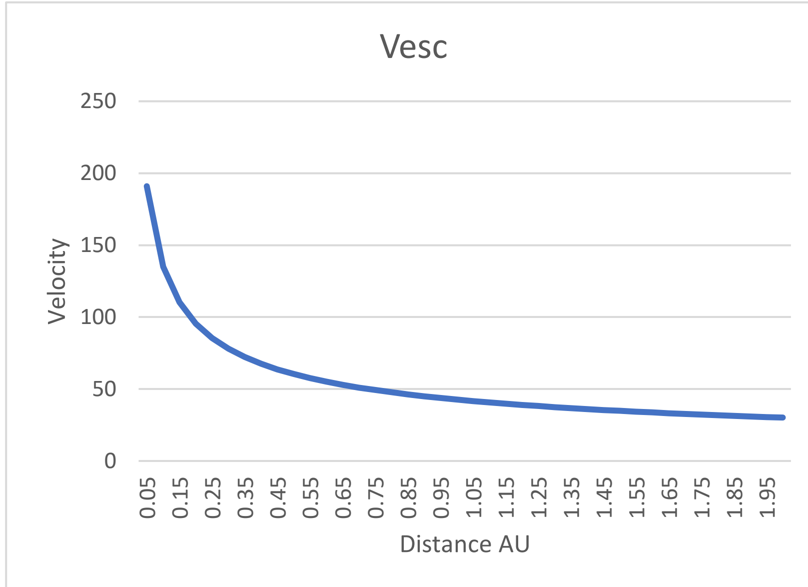


Figure 7-23 Solar Sail Velocity vs Solar Distance for Sail Loading of 1.53g/m²

μ=.9

σ=.752 g/m^2 = .000752kg/m^2

Then λ= 1.8838

If we use r=1 for the earth distance our Escape Velocity is:

$$v_{esc} = \frac{\mathbf{42.1(1.8838^{\frac{1}{2}})}}{\mathbf{1^{\frac{1}{2}}}}$$

$$v_{esc} = 57.783$$

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 μ=.9) we can get some very large velocities.

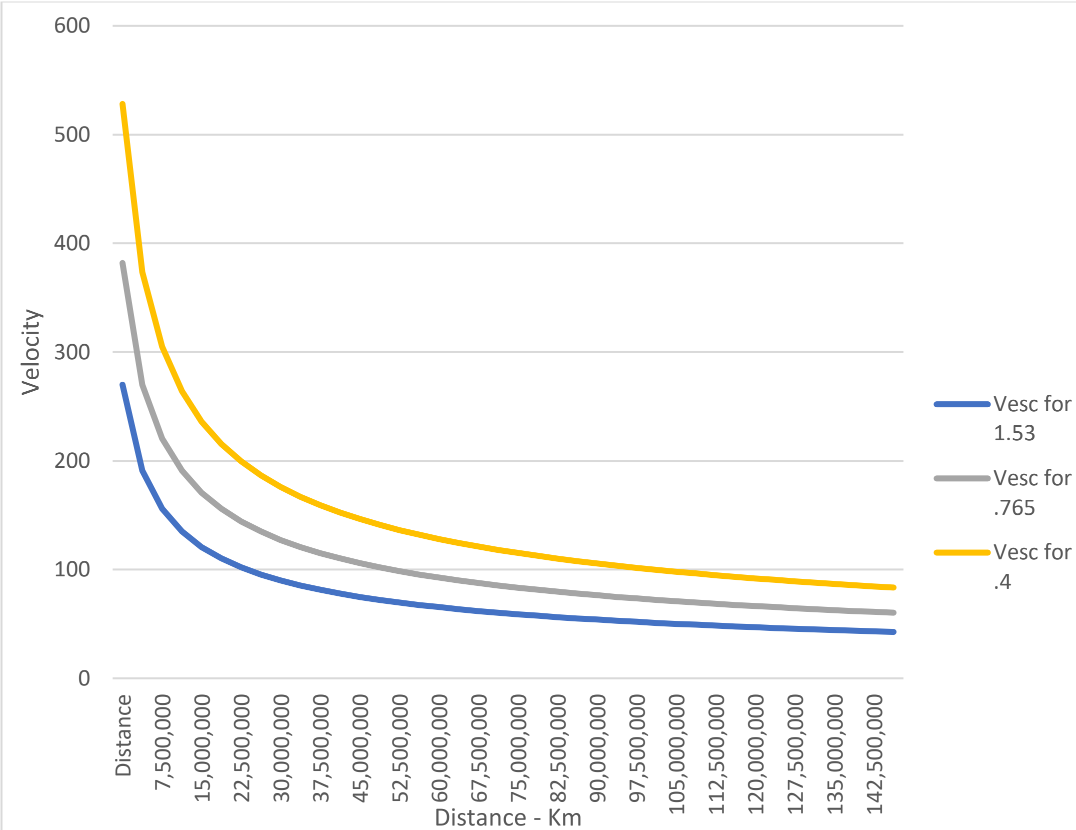


FIGURE 7-24 SOLAR SAIL VELOCITY VS SOLAR DISTANCE (EARTH ORBIT IS AT 150MILLION KM)

A generic version of this equation eliminates the earth distance velocity and suns illumination and makes it applicable to all point light sources:

EQUATION 7-30 $v_{\infty} = \sqrt{\frac{\left(\frac{albedo}{100}+1\right)Lr^2}{2cd\left(m_{craft}+\pi r^2 \rho_A\right)}}$

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)*

$\rho_A =$ *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 spares 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 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 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. If seems possible that solar sails would become practical when space elevators become technologically possible- many of the challenges are similar.

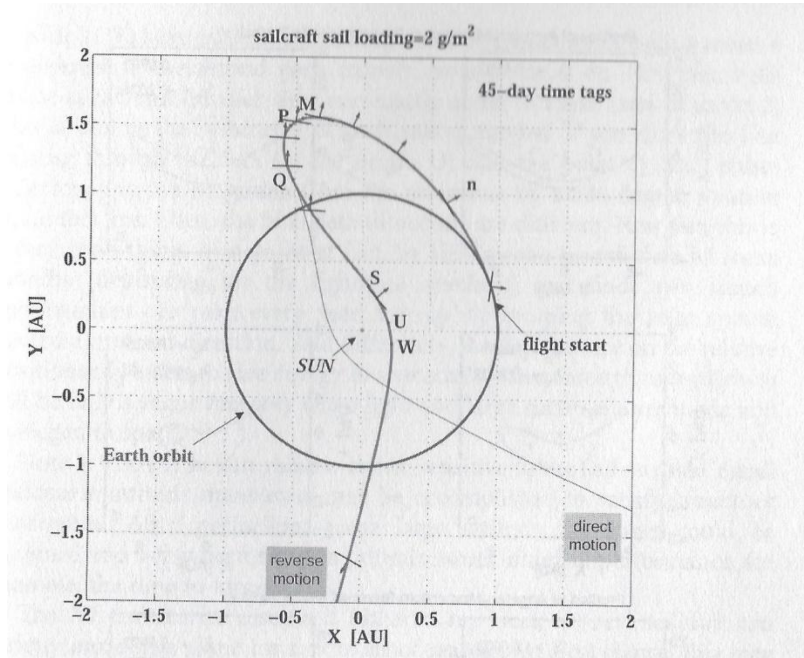


Figure 7-25 Approaching the Sun with a Solar Sail (Giovanni Vulpetti, 2008)

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.

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 Power and Electric Thrusters

Beaming power can be a partial solution to both high power requirements for electric thrusters or the problem of solar sailing as you get further from the sun.

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
- Fuel Specific

With beamed power, a very large laser beam based in our Solar System, would beam the power needed to the spacecraft. This eliminates the need for a huge powerplant on the spaceship. With vastly more power available, but minimal "power plant" mass, we can go with very powerful electric thruster engines and achieve very high performance.

In Chapter 5, the proposed nuclear power plant we picked was called Super Space Nuclear, and it created 20W/Kg of mass. Even with this capability a 1GW powerplant would weigh 50,000mt.

In the same chapter we also discussed the possibility of generating as much as 140w/kg if the solar cells were tuned to a particular laser light frequency with 50% conversion efficiency and the laser irradiance was twice that of normal sunlight. In this case the total mass of our solar cell power supply would be only about 7150mt- only 1/7th the mass of an equivalent nuclear power plant!

Laser Beamed Power for Solar Sails

We can also use laser beamed power to propel a solar sail. A beam of twice the solar irradiance would provide twice the thrust. As with sunlight and Raleighs Criteria, the laser beam intensity will decrease with distance but since its irradiance will be much higher, the solar sail will be subject to a longer period of acceleration. If we had a sail loading of 1.53g/m2, but were beaming twice the irradiance of the sun at 1au, our solar sail would receive twice the normal thrust and would follow the trajectory identified in Scenario 3.

Laser Beamed Power- Making this Work

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 3:

$$\boldsymbol{\theta = 1.22\frac{\lambda}{d}\ (in\ radians)}$$

Note from geometry (for small angles):

EQUATION 7-31 $sin\theta = \theta = \frac{d_s}{2r}$

So combing the two:

EQUATION 7-32 $\theta = \frac{d_s}{2r} = \frac{1.22\lambda}{d}$

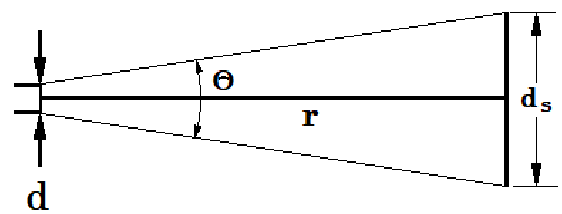


Figure 7-26 Geometry of Electromagnetic Radiation

We can rearrange our equation solving for d to determine the diameter of our laser aperture.

EQUATION 7-33 $d = \frac{2.44r\lambda}{d_s}$

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. Assuming our spacecraft needs 1GWe, and that our laser irradiance is twice that of normal sunlight- or 2800w/m2. Assuming 50% solar cell conversion efficiency we are back to effectively 1400 W/m2. This will lead to a total solar cell receiving area of 714,300m^2. If this were a circular receiver the diameter would be - or $d_s = 954m$. Note we can get an idea of r by asking how far will we be when we are done with our acceleration? For an example let us assume we are beaming out to about 100 million kilometers, or 1x10^{11} meters.

Let us pick a typical λ for light of 500nm (in the green part of the spectrum).

$$\lambda = 500nm = 5x10^{-7}\ m$$

$$d_s = 954m$$

$$r = 1x10^{11}$$

$$d = \frac{2.44r\lambda}{d_s} = \frac{2.44(1x10^{11})(5x10^{-7})}{954} = 127\ m$$

While this is certainly extremely large, it is not impossible to imagine. We certainly can conceive of a beam that is considerably wider or perhaps operate at a frequency somewhat higher to reduce our aperture somewhat. A wider beam would mean less intensity at the destination and more energy wasted. An additional challenge is the extreme pointing accuracy that would be required. Nevertheless, this should be technologically achievable.

The true difficulty is the amount of power required for the beam. With a 50% solar cell conversion efficiency, and all energy being captured we would need to beam 2GWe. In reality our spaceship might only intercept 10% of the energy, in which case we would need to beam 20GW. Furthermore, as mentioned in Chapter 5, laser conversion efficiencies from electricity to the laser beam are typically 20-40%, but with the anticipation that in the future perhaps 50% can be achieved. This means that our power plant may need to be as 40GWe. Sizeable anyway you look at it.

We will encounter many of the same issues with beamed power for Solar Sailing…

In the case of solar sailing, 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- of about 2800w/m^2. 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 m^2 or 19.5km in diameter. The power falling on this area would be:

$$P = \frac{w}{m^2}(A)$$

$$P = 2500\ (300{,}000{,}000) = 750GW$$

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 (ie not totally reflective) will emit photons out the back and reduce our thrust. A more complete equation for acceleration would be:

Equation 7-34 $a = \frac{\varepsilon\mu}{\alpha\sigma}\left(\frac{\sigma_{SB}T^4}{c}\right)$

Where

$a = acceleration\ in\ m/s^2$

$\varepsilon = emissivity$

$\mu = sail\ reflectivity$

$\alpha = absorption\ coefficient$

$\sigma = sail\ loading$

$\sigma_{SB} = Stephan\ Boltzmann\ radiation\ constant\ (5.67x10^{-8}\ \frac{W}{m^{-2}}/K^{-4})$

$T = Sail\ Temperature\ in\ Kelvin$

$c = speed\ of\ light\ \ (3x10^8 mps)$

The power required would be:

EQUATION 7-35 $P_s(W) = \frac{mca}{2\mu}$

To calculate the diameter of the sail ($d_{s)}$ we can use the equation:

EQUATION 7-36 $d_s = 2(\frac{A_s}{\pi})^{\frac{1}{2}} = 2(\frac{m}{\pi\sigma})^{\frac{1}{2}}$

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.

$$\boldsymbol{a} = \frac{.\mathbf{05}(.\mathbf{9})}{.\mathbf{15}(.\mathbf{756})}\left(\frac{(5.67x10^{-8})^4}{\mathbf{3x10^8}}\right) =.\mathbf{00768}\boldsymbol{m/s^2}$$

How much power would be needed?

$$P_s = \frac{150000(3x10^8).00768}{2(.9)} = 1.92x10^{11} = 192GW$$

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 .00768m/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 .000378kg/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.

Chapter 8 - Building a Spaceship

The popular cultural view of travel between planets has the crew operating their spaceship with no more complexity than one would have if starting their car. In movies and TV our protagonist hops in their spaceship, and with a few flips of some switches and the pressing of some buttons they launch. They arrive at their target world/space station (that may not even be in our solar system) within hours, days or at worst a couple of weeks. The ship has artificial gravity, can be refueled quickly and easily, and has unlimited power. Cosmic radiation is never mentioned or considered a problem. They can land on any planet, with or without an atmosphere and with or without a runway or sometimes even without a landing pad.

The reality is very different:

- Lifting off from a large moon or planet requires a large amount of power and high speeds. Getting into Earth orbit from the ground requires almost 8kps of velocity.
- Vast distances. To cross the vast distances to other planets, moons and asteroids, ships have to move at tremendous speeds, which require huge amounts of power- often many Megawatts. Power sources for propulsion are usually chemical rockets and power for heat or electricity is provided via RTGs, solar or fuel cells. Future passenger and large space stations may have the nuclear or solar power provide the power for propulsion as well as heat and electricity.
- Long Voyage Times. Except for the moon, most ships, taking the most efficient Hohmann transfer orbits, take almost 6 months to get to Mars and several years to get to any of the more distant planets or asteroids. With voyage times of many months or years, ships with large numbers of people will need to be very large, and have extensive recycling capabilities for food, water and air as well as to provide for artificial gravity. Except for earth orbiting space stations and the moon that can be reached within a few days, space vacations will not be possible.
- Physical Fitness- High acceleration forces during launching or landing on earth requires personnel to be relatively fit. On launches, these high acceleration forces will be followed by an uncomfortable period of adapting to zero g. Zero g frequently leads to vomiting and motion sickness that will last for several days. Furthermore, prolonged exposure to reduced or zero gravity will have a severe impact to health. This can only partly be ameliorated by an extensive space exercise program.
- Artificial gravity via centripetal forces can be done but will make the ships larger and more challenging to design and build. These ships may NOT be able to land on target planets/moons.
- Intense radiation. In an unprotected ship traveling outside the earth magnetic field, the crew will be exposed to intense radiation, in many cases reaching what would be considered a lifetime radiation dose in only a few months.

In our dreams ship we would have a ship that accelerates at 1g until the halfway point, and then flip around and decelerate for the second half. While providing for a tremendously fast voyage, this also has the advantage of providing artificial gravity without the need for a rotating habitat. Our ideal spaceship would have a very powerful active cosmic ray shield along with some lightweight passive shielding- though the short travel times will make this issue less severe. We will look at the capabilities of such a rocket later in this Chapter.8

Spaceships are normally propelled by rocket engines. Rockets refer primarily to the part of the vehicle that contains the fuel and engine, and are frequently separate from the spaceship- but they do not have to be. The SpaceX full up two stage vehicle is referred to as a rocket. The first stage is a rocket, containing most of the fuel and engines for lift off. It will never reach space but instead provides the initial velocity to the 2nd stage at which time it flies back to a recovery tower to be refueled. Conversely, the SpaceX second stage is both a rocket and a Spaceship. It has propulsion elements like a rocket, is able to land back on the earth but also land on another planet, and travels through space. Rocket engines historically refer to high power, high thrust, and relatively short duration devices. Spaceship can also use low thrust engines like electric thrusters or ion engines. These can run for weeks, months or years and are not usually referred to as a rocket engine but as thrusters.

Despite the lack of accuracy on the challenges of space travel in popular culture we can speculate on what a realistic interplanetary spaceship would look like while remaining within the laws of physics and the realm of engineering possibility. Rocket engines need two types of fuel- those for power and those for reaction mass. A chemical rocket can use the same material. Combining oxygen and hydrogen can create both power and provide reaction mass. However, in other cases the power fuel (i.e. a reactor) will be different than the reaction mass. In either case, ideally the "Fuel" as well as the reaction mass should be a widely available resource. For fission power, Uranium fuel is usually the preferred material- though this requires extensive mining and processing. For reaction mass, hydrogen is preferred since it is relatively abundant throughout the solar system, and because its light atomic mass means it has the highest specific impulse. Depending on the propulsion system for reaction mass raw material like regolith or rock may be an option for certain types of rockets.

Spaceships will come in two basic types- those that can reenter an atmosphere for deceleration, and those that cannot. Most of these spaceships, both atmospheric and non, will have engines powerful enough to lift off directly from a planet, moon or planet- except for the Earth. At least for the near and mid-future, earth launched spaceships will need a larger first stage rocket to help propel them into orbit.

Besides spaceships designed for atmospheric reentry and those without, their will also be further iterations for those that are for long term missions. For longer missions they may rotate to provide artificial gravity. One additional limitation is that for Spaceships returning to Earth may be prohibited from having large nuclear reactors or nuclear engines.

Mission to and From	TPS	Gravity	Power Source
Earth to LEO	Yes	No	Chemical
Earth to L4/L5	Yes	No	Solar
Earth to Moon	Yes/Maybe	No	Solar
Earth to Mars	Yes/Maybe	Maybe	Solar/Nuclear
Moon to L4/L5	No	No	Solar
Moon to Mars	Yes	Maybe	Solar/Nuclear
Moon/Mars to Asteroids	No	Yes	Nuclear
Earth to Titan	Yes	Yes	Nuclear

Table 8-1

Earth to Orbit

Rockets used to launch from Earth to Orbit are an old technology that has been around for over 70 years. Humans have figured out both how to reach orbit, as well as survive reentry. We have built multistage rockets, space capsules and aerodynamic return spacecraft. Because of the relatively high gravity of the earth, all Spaceships to earth orbit have been multistage rockets- a dedicated and disposable rocket (or rockets) to give the orbital payload or spaceship enough velocity to get to orbit.

Over fifty years the primary improvement in mankind's quest to colonize space had been an improvement of launch reliability. However, over the last ten years we have also been seeing a lowering of price to orbit. Any colonization attempt or space-based infrastructure (like orbiting power stations) needs to continue this trend.

Space X Starship and Interplanetary Successors in the 21st Century

In Table 8-2 I tried extrapolating a realistic list of interplanetary rocket ships that could be built over the rest of this century. I begin with chemical rockets and then include Nuclear. We see that chemical rockets will likely be limited to about 11kps (with aerobraking we can add about 7kps), but that is the limit.

Beginning with the Starship v3 and v4, I go into future enhanced rockets and to more advanced and speculative designs. Even though the specific design of a rocket will depend on the target and payload, we can make some good approximations of what an interplanetary spaceship would look like using Elon Musk's SpaceX Starship as a starting point. The planned Starship v3 will likely have a dV of only about 8kps and a stretched starship (v3) may achieve a dv of 9.5kps. In Chapter 3 we showed three classes of spacecraft needed- those with dv of 10kps or less, those with 10-13kps, and those needing more than 13kps. The current Starship is in the first class. I kept the payload for all configurations at 100mt:

	Fuel	Dimensions	Empty Mass/ Payload/ Fuel Mass (mt)	MR	Performance kps	Comments
Starship v3	Metha-lox		100/100/1500	8.5	8.025+7	In production; Thermal Protection System (TPS); Mars; L4/L5
Starship v3a	Methalox		90/100/1510	8.895	8.218	No TPS, no Rapture Sea Level engines; Moon, Some Asteroids, L4/L5
Starship v4	Methalox		110/100/2290	11.952	9.289+7	2028 production; Active Radiation Protection; Mars
Starship v4a	Methalox		100/100/2300	12.5	9.471	2030 production; no TPS; Active Radiation Protection
Starship v5	Methalox		115/100/2400	12.163	9.369+ 7	2036 production
Starship v5a	Methalox		105/100/2410	12.707	9.548	2038 production; no TPS
Interplanetary SS v1	Hydro lox		120/100/2200	8.955	9.891+ 7	Designed and built in space; Can't operate from Earth
ISS v1a	Hydro lox		110/100/2200	9.333	11.01	No TPS
ISS v2	Hydro lox		125/100/2400	9.696	11.085+ 7	

ISS v2a	Hydro lox		115/100/2410	10.091	11.29	No TPS
Nuclear ISS v1a	Hydrog en		150/100/2400	10.6	20.846	Solid Fuel (2050)
Nuclear ISS v2a	Hydrog en		250/200/2500	4.333	143.85	Fusion (2100)

Table 8-2 Empty mass is mass of spacecraft plus payload, not including fuel; Isp for Methalox is 382s (3750mps) and Hydrolox 460s (4,512 mps); Nuclear ISS is 900s (8830mps); a hypothetical Fusion powered ISS with a specific impulse of about 10,000 (98100mps) is included to show the tremendous potential of portable fusion rockets; if TPS is included 7kps of deceleration is assumed.

Items with an "a" are ships without thermal protection system (TPS). TPS can be used to return from space stations at L5, moon returns, as well as the asteroids back to Earth. For outbound missions TPS will be restricted to objects with a substantial atmosphere including Venus, Mars, and Titan. A TPS adds some mass to the empty ship- It is assumed about 10mt, which reduces the rockets dv, but this is more than made up for the deceleration dv on arrival at target. A reasonable capability for a reuseable heat shield would be to shed about 7kps of velocity. Those ships without TPS will either have a (slightly) greater fuel capacity and therefore performance or will be able to carry larger payloads. An atmospheric deceleration can both be used to decelerate a spacecraft for landing (as with Mars or Venus), or by skimming through the atmosphere to skim off excess speed so the spacecraft can go into orbit or land on a moon. Also, even for missions to planets or moons that do not have an atmosphere, the TPS system might be required if they are returning to Earth. Note that for large planets like Jupiter or Saturn their large gravitational fields mean that approaching spacecraft, even if initially approaching at only a couple of kps, will gain velocity and be near escape velocity when hitting their atmosphere. In Jupiter's case, space ships will be approaching at about 60kps, and for Saturn about 35kps, which makes using the Jupiter or Saturn atmospheres impossible for a reusable heat shield (though this make become available in the future as technology improves).

Starship v3 are estimated specifications for the Starship version which I anticipate being flown in 2026 has been stated to carry 25% more fuel than v2. This will likely be the first practical interplanetary spacecraft. All whole integer Starship versions have Thermal Protection Systems (TPS). The target payload for the v3 is 200mt into orbit but I assume for standardization of my performance calculations, 100mt will be the normal payload for interplanetary voyages. The intent with the Starship bound for Mars is that they will use atmospheric drag for a majority of their deceleration- whether arriving at Mars or returning to the Earth. The v3 spacecraft appears suitable for Moon, Mars, and possibly some Asteroids as well as L4/L5 points. The v4 versions will be suitable for Venus and Titan and perhaps, Neptune's and Uranus' moons where they can use the gaseous giant's atmosphere to decelerate. More distant objects are also possible, but if we use Hohmann transfer orbits and gravity assists the mission times are several decades. Regardless, even the v3 version will take several years to reach Jupiter, the closest of the outer planets. However, unless they are part of a larger assembly, these ships will not have artificial gravity.

As can be seen when Starship v3 and v4 reach maturity no further improvements can be made using Methalox other than substantially increasing the MR. Spaceship performance will be around 9.5kps, and perhaps with reduced payload or decreased starship structural mass, stretched to 10kps. Interplanetary Space Ship v1 is a proposed Starship class ship that uses LH and LOX, and because of the higher specific impulse, either higher velocities will be obtained or lower Mass Ratio allowing for greater payload. However, Hydrogen in particular is very difficult to handle and requires large, extremely insulated tanks for storage so will tend to increase the mass of the spacecraft negating much of the higher specific impulse. The extremely low density of liquid hydrogen requires a far larger volume to store the same mass as Methane. For this reason, Hydro lox rockets will require far larger spacecraft, so I have increased the standard diameter over the Methalox spacecraft to 12m. I foresee both ships working in parallel. The Methalox Starship would be used for Mars where the Martian atmosphere will be used to refill the methane and oxygen tanks, and the InSS on bodies that have water from which the hydrogen and oxygen can be obtained.

The striking thing about the rocket equation and all the configurations we looked at is that without nuclear engines, getting a spaceship above a dV of 10 kps is almost impossible.

How will these spaceships be powered? The intent for the Starship v3 and v4 is to use solar panels. This should work for the lunar and mars voyagers. However, for more distant destinations, and for greater flexibility on future voyages, nuclear power will be needed (see chapter 4). Eventually small nuclear fission reactors will be developed for use on ISS's- ranging from 10kw to 100kw.

Nuclear Thermal

Nuclear thermal, because of their higher impulse, are practical for much faster spaceships. Their problems are:

The Nuclear Thermal that have been developed to date are solid fuel.

Cyclers

Cyclers are a logical solution to many of the challenges of building an interplanetary spaceship. A cycler is essentially a large space station that orbits the sun in an elliptical orbit with its perigee inside the orbit of one planet (usually the earth) and the apogee outside the orbit of the destination planet. The space station would have both radiation protection and could have artificial gravity. Because by definition cyclers need to be in orbits that are relatively stable, requiring minimal orbital adjustments, and the need to "cycle" on some sort of schedule, the planets that they are to cycle between must be a whole fraction of one of the planets orbits. The Earth/Mars cycler is the most frequently cited as Mars orbits the sun about 8 times for each 15 earth orbits. Jupiter cyclers have not really been looked at as the orbital parameters of the Earth/Jupiter are not conducive to repetitive, stable elliptical cyclical orbits and would typically involve very large dVs- much larger than that required for a Hohmann transfer orbit. Cyclers have been considered for Venus and would probably be very beneficial, assuming Venus is ever developed into a viable target. In the case of Mars, multiple cyclers would be preferred to increase the flexibility of missions. Cyclers would not be helpful in shipping cargo as they require higher dVs than that of a spaceship doing a Hohmann transfer. Typically, since they are on a more elliptical orbit extending past the orbit of Mars, the journey time would be reduced, but the reduction is slight- usually about a month or two. More importantly, the cycler, if built large and permanent, will be much more massive than a Spaceship, and as such will have much higher radiation protection, and higher comfort level as can be built with artificial gravity.

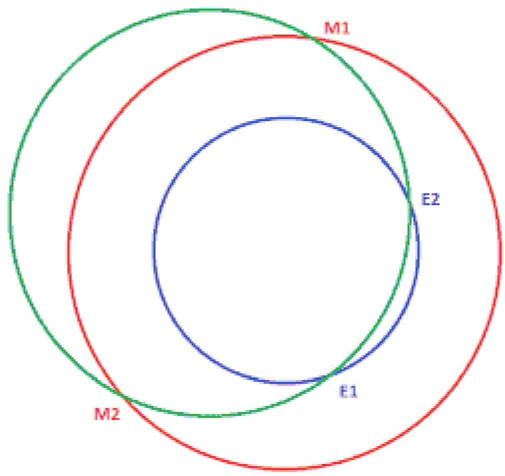


Figure 8-1 Cycler Orbit; Blue is Earth Orbit, Red is Mars Orbit and Green is cycler

With this scheme, a relatively small, unshielded shuttle carrying colonists or travelers will depart from the LEO at high speeds and hook up with the Cycler. They will disembark on the cycler and live for the duration of the outbound voyage- in the case of Mars, usually around four months, after which time they would disembark back on their shuttle for atmospheric deceleration at Mars. Cyclers will travel very fast in their elliptical orbits, and to intercept a Mars cycler as originally designed, would require a 6.7kps dv for an object orbiting the sun at the Earths distance, and to catch a return trip back from Mars, a 9.8kps dv would be required. These are far higher velocities than would be required for a Hohmann transfer orbit. However, a Hohmann Mars mission would typically take one to four months longer, plus the cycler would have far lower radiation levels due to much more extensive shielding and reduced travel time. If the cycler method becomes the defacto method of traveling to Mars, I could conceive of very large cyclers picking up perhaps half a dozen colony ships and 500 passengers, and dropping them off five months later at Mars.

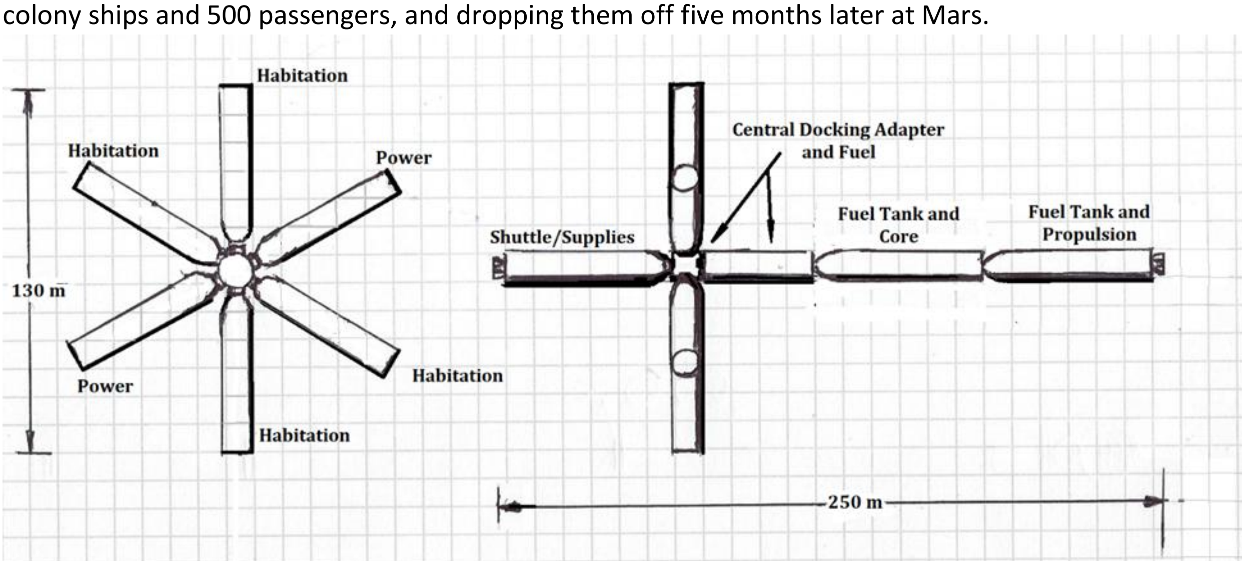


Figure 8-2 Possible Configuration for Mars Cycler

The Uber Interplanetary Rocket

There is nothing in the laws of physics that would prevent building a “Uber” rocket - however from an engineering point of view this capability would be challenging if not impossible- at least over the next century. The primary requirement for an Uber spaceship is tremendous, controlled power with low mass. With tremendous power you can frequently reduce your reaction mass by substantially increasing your exhaust velocity.

To give some illustrative examples of the capabilities of the sort of an Uber ship that can constantly accelerate at 1g or ½ g for days on end :

From Earth To	Million km	Travel Days 1g	dv	Travel Days 1/2 g	dv
Mars	100	2.34	1980.91	3.3	1,401
Jupiter	700	6.18	5240.99	8.7	3,706
Saturn	1300	8.43	7142.27	11.9	5,050
Uranus	2700	12.14	10293.10	17.2	7,278
Neptune	4400	15.50	13139.86	21.9	9,291

Table 8-3 The Uber Interplanetary Constant Acceleration Rocket

Impressive indeed. Such a vehicle would not need much cosmic ray protection since the longest missions would last less than a few weeks (if the speed of light limit did not exist you could even get to the nearest stars in only a year or two). However, the dv column shows us how difficult these performance numbers would be- at 1g by the time you reached Neptune you would be traveling at over 13,000kps where a current multi-stage rocket, launched into earth orbit is traveling at only 8kps and had to have two or three stages to do it. This sort of technology does not and probably never will exist. The rockets being designed today have only one one-sixteen hundredths of this performance. To drive this point home, since energy is the square of velocity, an Uber rocket that could go 13k kps will need about 2.6million times more energy- or power per kg of mass.

Even though a rocket of this capability is beyond our engineering capabilities, we can still conceive of a more reasonable rocket that with some large increases of performance over the next century with only modest extrapolations of technology.

A Realistic Uber Interplanetary Rocket in the late 21st Century

For the outer solar system to be opened for colonization, hyperbolic transfer orbits will be required to cut in half or more the transit times. Besides the need to shorten manned flights for shear practicality, these rapid spaceships will reduce exposure to cosmic radiation. In addition, even the short duration flights may last a month or more, and some will last years. This will require very large and massive spaceships, ideally with artificial gravity and perhaps carrying hundreds and perhaps thousands of people.

There are four options for propulsion- chemical, nuclear thermal, electric powered by nuclear power (either ion, electrostatic or mass driver), or what I call a hybrid rocket which would use a nuclear reactor to create the rocket fuel as well as provide power for electric propulsion.

Our next generation rocket after the current SpaceX designs, will use a hybrid propulsion system with a large nuclear power plant.

The rocket, if used for the inner solar system (Moon, Mars, Mercury, Venus) would have about 8-9kps capability from Low Earth Orbit (LEO- which we will specify as 300km above the Earths surface). For more distant targets, as shown in Chapter 2) the spaceship will have dV capabilities of 13kps. If going to Mars or Venus, or returning to Earth it will have a Thermal Protection System (TPS) able to decelerate and remove 7kps of velocity. This spaceship may need to be able to land on a moon or small planet- in this case, Mars would be the most challenging because of it relatively high gravity. This requires rocket thrust sufficient to land and take off the surface of Mars. The ship will also have active radiation mitigation sufficient to reduce cosmic radiation be 50% for the Inner Planet and have combination of passive and active for the Outer planet ISS that would reduce radiation 90%. Rockets would have to be relatively easily refurbished and refueled. For Spaceships going on missions more than 6 months, the rocket should have artificial gravity.

Note that rockets with 20kps capabilities open up the whole solar system. If we applied our whole 20kps impulse at the appropriate time while in orbit around the Earth we could get to Neptune in 3 years- however our speed at Neptune would be extremely high, on the order of 36kps. Aerobraking can be used to bleed off speed on arrival to either minimize the dv needed to land, or to minimize the dv to enter orbit but no material we currently have would successfully aerobrake to reduce our speed by over 30kps. More typical are approach speeds of 7 kps or slower. Higher aerobraking techniques can be used but these are not for reuseable spacecraft and often subject payloads to very high g loads. In the case of the probe that explored Jupiters atmosphere it entered at about 47.5kps, and experienced a peak of 230g.

Without aerobraking all arrival velocities will need to be bled off by the rockets. Even with aerobraking, rockets may be needed to circularize orbits or to actually land on the surface. All this eats into our fuel margin.

There are three phases of rocket flight that require conflicting requirements. Most missions will begin on a planet/moon or asteroid, or in orbit around one of these. To break away from a gravitational field it is best to have a high thrust engine- this minimizes gravity drag. This requires a traditional chemical or perhaps a version of the proposed nuclear thermal engine. Ideally, we could use this thrust to propel us directly to our target, but the reality is that this may require an impractically large initial impulse (6-8 kps) which will drive our mass ratio very high. Keeping in mind that on arrival we will need to enter orbit, dock or land and additional 1-4 kps thrust will probably be required. The rocket equation tells us that for the best chemical fuels a MR of 10 will be required to give us a 10kps delta, and a MR of nearly 16 for a 12 kps delta.

Nuclear thermal rockets give a sizeable performance improvement. It may be able to increase a solid nuclear engine up to 1000Isp. However, this assumes Hydrogen is for the reaction mass- the specific impulse is quickly reduced as heavier elements are used. As mentioned, Hydrogen is extremely hard to handle- it needs to be kept close to absolute zero, will tend to leak past any seal or gasket, and is very voluminous, requiring extremely large and extremely insulated tanks. Furthermore, if Hydrogen is the fuel, where will it be obtained? In the solar system most hydrogen is locked up in the atmospheres of the gaseous giants where it is unreachable. Most of the hydrogen we can reach is combined with oxygen in the form of water. Hydrogen, through electrolysis can be easily separated but this requires a lot of power. Furthermore, while Nuclear thermal do provide a lot of thrust compared to Electric Thrusters, they provide a lot less than Chemical engines.

Electric Thrusters and Ion Engines have their own challenges (see Chapter 6). While very efficient if voyage times are measured in years and operated outside of a large gravitational field they provide very low thrust, usually measured in fractions of a newton. You can increase their thrust but this requires large amounts of power. Furthermore, the traditional fuels are noble gases, usually Xenon or Krypton which in general are relatively rare. Other materials can be used (like Hydrogen) but as with Nuclear thermal, Hydrogen provides even less thrust than the noble gases. Electric Thrusters will not be able to be used for landing on a moon, planet or asteroid, they are too weak. However, when paired with a traditional engine and a powerful powerplant, they have advantages that can't be ignored.

For a spacecraft with a dV of 10 kps, we might assume that it will use most of this capability in one thrust event. However, for many missions this will not be accurate. A spacecraft may launch from the moon, or planet and then orbit for a days to check on systems and wait for the proper trajectory. A mixed mode spaceship can get around some of these limitations- mixing high thrust for takeoff, breaking orbit or landing, but electric propulsion system to increase its velocity in deep space and shortening travel times.

None of these ships will be able to take off from Earth- that is too hard of a challenge and requires a dedicated launcher. Mars, with a gravity 1/3 Earths is probably the highest target we will need to take off from which means our engines will need to 1/3 the thrust that would be needed for an earth lift-off.

To lift off and go into orbit around the moon only takes about 1.9kps. Mars is much harder- closer to 4.2. An asteroid much less. Some fuel must be saved to either go into orbit around a target, rendezvous, or land. Even an atmospheric entry into a planet with atmosphere can slow the spaceship down but some fuel will still be needed to land.

We could also consider a mixed mode, hybrid spacecraft which has most of the reaction mass stored as water. The spaceship was built with LOX and LH tanks only enough to give a dv of about 4.5 kps and an initial MR of slightly under 3. Additional fuel will be created from water tanks via electrolysis with energy supplied by a nuclear power plant. In addition, between the initial lift off and arrival, we will apply additional thrust via electric thrusters. Based on the low thrust, this sort of mission is best for more distant planet that requires multi-year voyages.

		Configuration #1			Configuration #2		
Phase	Exhaust Ve	dV	MR	Mass in MT Start/End	dV	MR.	Mass in MT Start/End
Start	4,400	4.5	2.8	2400/850	3.0	2	1200/600
Coast	40,000	7.77	1.214	850/700	7.3	1.2	600/500
Landing	4400	4.5	2.8	700/250	3.0	2	500/250

Table 8-4

In these hypothetical examples, we have a very large and capable ship with a 1 MW power supply. With configuration #1, it would take off using about 1550 tons of hydro lox, completely emptying its tanks. Once on its way it will switch to its Electric Propulsion. This will be an improved version of current designs like VASMIR and will use liquified Argon. The extreme efficiency electric propulsion means that we only have 150tons of Argon but will get a dV of 7.8 kps. Normally even though we will be in interplanetary space, electric engines are not very efficient due to gravity losses from the sun. However 1 MW power supply is many orders of magnitude larger that what have used in the past. We will assume some efficiency gains over the VASMIR and by using Argon we are assuming we can get about 40 nt of force, astronomical for electric propulsion but feeble compared to Chemical engines. This will start us off with an acceleration of our 850mt ship of 4.71×10^{-5} mps2. Over the course of a day our velocity will increase by just over 4mps. Using our Mass Flow Equation 7-14, we can calculate how long we will be thrusting:

$$\dot{m} = \frac{F}{v_e} = \frac{40}{40{,}000} = \ .001\ kg/sec$$

With 150,000 kg of Argon, this would take about 4.8 years of continuous thrusting.

Depending on the mission, we may not need this full amount of fuel but regardless this is extremely leisurely and will incur a lot of gravity drag. Clearly, we need to either lighten our ship, or increase our reactor size. I think we need to do both. In addition, if we lower our Isp but keep our input power the same we can increase our thrust by the relationship for Equation 7-19:

$$F = \frac{2nP_{in}}{v_e}$$

If we double our reactor output while keeping our mass the same we will double our thrust to 80nt. In Table 30 Configuration 2, we have tweaked various parameters to try to come up with a more reasonable design. We lowered our Phase 1 and 3 dV requirements to 3 kps- in most cases for take off or landing this should be sufficient. We can use our electric thrusters to reduce approach velocity, and with our most demanding gravity planet is Mars, atmospheric breaking can reduce required rocket dv. We will also lower our Argon reaction mass to 100mt. We now will have an acceleration of 1.33×10^{-4} mps or 11.52 mps per day. Our mass flow is now .002 kg/sec, and with 100 mt of Argon, we would expend all our fuel in just under 1.6 years. Note by reducing our Isp to only 2000sec, we can double our thrust and fuel consumption again, though we will half our Phase 2 dv to only 3.5kps.

The advantages of a hybrid scheme are several. For one, you will be storing less of the dangerous and difficult to store LH. In addition, your LOX tanks will also be smaller. Furthermore, most of this fuel/oxidizer will be burned within the initial few minutes of liftoff. Most of your reaction mass that will need to be stored for the duration of the mission will be stored as relatively easy to handle, minimally insulated, water and Argon. Water is about 15x denser than liquid hydrogen, and only slightly (15%) less dense than oxygen so on balance your rocket will be smaller. The water is also one of the best shields against Cosmic Rays.

The mass of the nuclear reactor is a negative but in general you would have to have a power supply anyway, though the requirement for electrolysis as well as electric thrust will just make your requirements somewhat larger. Water is relatively easy to handle, safe, has well known properties, and very common in the solar system, making it an ideal fuel when we need to refuel. Finally, water provides a very effective cosmic ray protector. Several large tanks, appropriately placed, could help reduce the cosmic ray shielding requirements of the passengers.

What would a hybrid rocket look like and how would it operate? Building on Configuration 2, we are looking at something with the following specifications:

	Uber1	Uber2	
Payload(mt)	100mt	200mt	
Mass Empty (+Reactor)(mt)	150mt	300mt	50 mt is the reactor
Mass Empty Oxygen Tank	3.5mt	7.1	
Mass Empty Hydrogen Tank	13.3mt	26.7mt	
Total mass (Fuel and payload)	1200mt	2400mt	
Reactor Mass	50mt	100mt	

Reactor Output	2 MW	4 MW	40W/kg
Total dv	13.3kps+7		7kps from aerodynamic deceleration
Specific Impulse	460		HYDROLOX for Take off and Landing; Aerospike engine
Specific Impulse	4000		Argon
Thrust of main engines	9,000,000nt	18,000,000nt	Enough to lift fully loaded ship off Mars at .8g
Thrust of Electric Thrusters	80nt	160nt	
Total Payload and Empty Mass	250mt	500mt	
Reaction Mass	2300 (2200/100)		Hydrolox and Water/Argon
Oxygen Tank Storage	514	1030	
Hydrogen Tank Storage	86	172	
Water Tank Storage	250	500	
Stage 1 (Total Mass/Empty Mass)	1200/600		2.5kps
Stage 2	600/500		6.3 kps
Stage 3	500/250		3
Artificial Gravity	.11g	.125g	3 rpm
Passenger Volume	440m3	1000m3	
Active And Passive Shielding	5 MV plus		
Passive water shielding	.5m		Water Shielding around all habitable areas.

Table 8-5 Proposed Interplanetary Space Ships for 2075 and beyond

In this space ship, an aluminum hydrogen tank of the required size would mass about 13.3 tons and the Oxygen tank would mass about 3.5mt. The habituated section consists of a pressurized torus with a radius of 10m (but with the floor at 11m) with the whole spaceship rotating around its axis at 3rpm to give about 1.08mps gravity. This inhabited torus would be enclosed within an outer torus of water that would be about 4m in diameter. Note that this spaceship might be made of aluminum, stainless steel or both. Initially I conceive as a majority of the spaceship to be aluminum but the base of the ship to be stainless. However in a mixed material design, different coefficients of expansion as well as galvanic corrosion would have to be addressed and we might want to switch to an all Stainless Steel or all Aluminum. Either way, aluminum, while considerably lighter than SS, is also much weaker than cold worked SS, so the actual mass of the empty ship may not change that much.

The habitable area would be about 440m3. Depending on how many people we needed to pack into this ship, we could take anywhere from 4-40 people for voyages up to 6 months. Artificial gravity will be provided by rotating the ship at 2rpm around its axis. The ship has abundant power, and excess heat from the ship and reactor would be released by four large clam doors opening up at the sides of the ship. The Electric thrusters would be at the bow of the vessel. Active cosmic ray protection would be provided with everything above the clamshell doors being positively charged, and that below the doors negatively charged.

This is a fairly small Uber Rocket, but the general scheme can be scaled up to twice as big if needed- the Uber2. The Uber2 would have a diameter of about 30m, with LH and LOX tanks of 16.7m and 12m, and a mass of 26.7mt and 7.1mt. We could increase our reactor to 100mt and 400MWe. If we are not interested in atmospheric entry, we could eliminate the bottom heat shield, and simplify the aerospike engines, perhaps saving 25mt that can be used for increased performance.

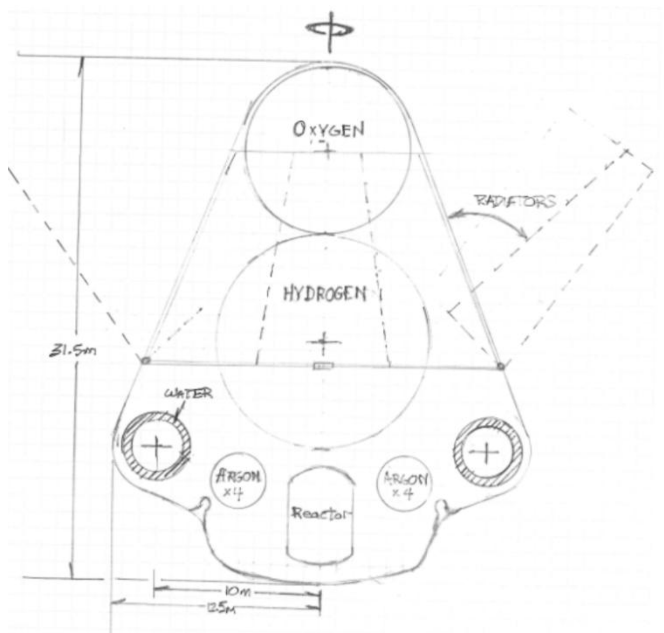


Figure 8-3 The Uber Rocket 2075. The Hydrolox Engines are either an Aerospike or Detonation type annular type.

There are other ways of improving our ship's performance. We can consider the Oberth powered maneuvers, as discussed in Chapter 2, which can achieve spectacular velocities with high thrust nuclear or chemical rockets. If we use a 10 solar radii flyby of the sun with a dv impulse of about 10 kps we would achieve a velocity change on the order of 60kps… at this rate the outer solar system, including objects like Pluto or Eris, could be reached in only a few years. However, these velocities are so high that a huge delta v would need to be applied at our target to slow down and be captured. If arriving at Jupiter, Saturn or Titan, we can use aerodynamic breaking but the dvs are so large (as large as 50kps), that the thermal protections system needs to be much more capable than those currently designed. This is far larger than any of our ISS spaceships considered except perhaps the speculative Nuclear ISS v2 fusion design. Because of this the Oberth maneuver seems to be more suitable for one-way interstellar payloads out of the solar system.

In a hundred years chemical rocket engines will be little changed from what we have now- their efficiencies are frequently over 90% so there is little room for improvement. These engines will likely be more reliable and slightly less massive, but their performance will be about the same.

Most of our spacecraft technological improvements will be in the areas of power. Nuclear reactors will be on most ships and will be relatively small and compact, put out MW of electric power, requiring refueling every decade or two. These power plants will power life support, ion/electrostatic engines, or separate water into rocket fuel for our dual mode hybrid rocket.

We will likely have nuclear engines and much more capable electrostatic engines. The nuclear engines will be capable of specific impulses of 1000, or more aggressively if considering liquid or fusion rockets, perhaps much higher. Ion engines will likely be much larger, able to handle far more power. In this case, a large 1MW powerplant may be able to provide ten or more newtons of thrust.

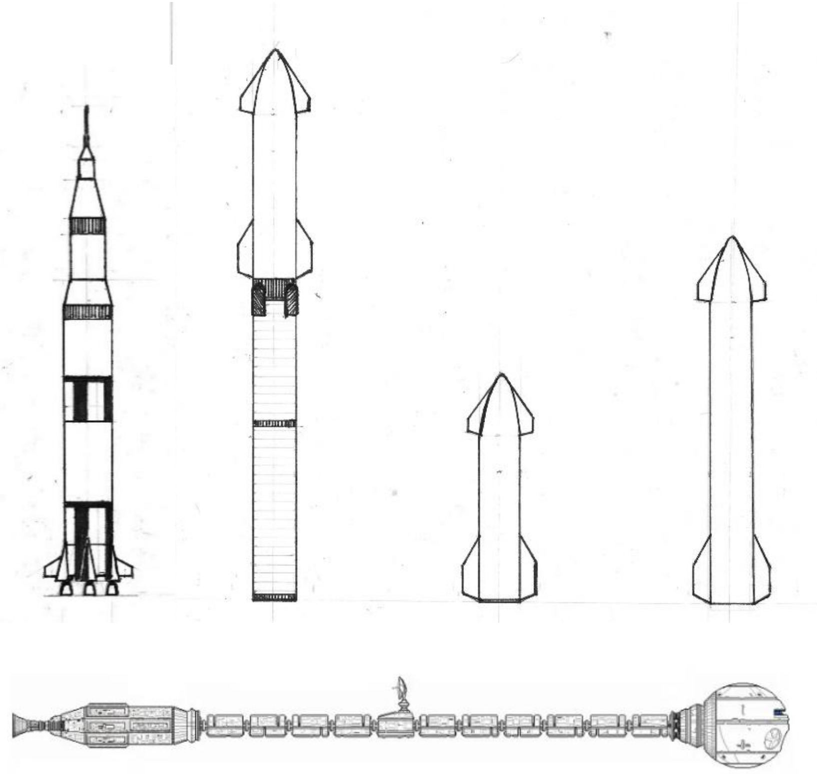
Finally, the generally low performance numbers of Chemical rocket will limit their use to the Earth, Moon and L5 locations, as well as Mars and perhaps some asteroids. Even with Mars, it is likely that most astronauts will use rockets to rendezvous with Cyclers (see next section) rather than as stand-alone vehicles to Mars. For deeper space missions' various chemical rockets may be suitable for some unmanned cargo missions but for crewed missions, the voyage times are too slow. Nuclear thermal rockets promise to half the journey times and will likely be required for personnel, with Electrostatic Ion or Mass drivers being used for cargo for those more distant planets.

Based on Table 32 and Table 33, I see four standard types of spaceships divided by their rocket types and the fuel they will use. These will be designed to carry passengers and cargo with a target of 100mt:

Fuel		Performance	Destinations	
Methalox	No TPS	8.5	LEO to Moon, L4/L5	
	TPS	8.0+7	Mars, Earth Return from Moon/Mars, L4/L5, Titan, Cycler	
Hydrolox	No TPS	10	LEO to Moon; Asteroids, L4/L5	
	TPS	10+7	Mars, Earth Return from Moon/Mars, L4/L5, Titan, Cycler	
Nuclear Thermal	No TPS	12	LEO to Asteroids; Moon; Mars	
Hybrid	No TPS	14	LEO to Asteroids	
	TPS	13+7	LEO to Mars; Titan	

Table 8-6

Table 8-7



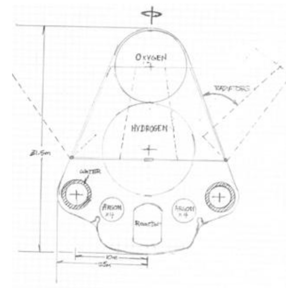


Figure 8-4 Saturn V, Fully Stacked Starship v3; Orbital Starship v3, Orbital Starship v4 (stretched); Uber Hybrid Rocket

Space Elevators

Space Elevators' development will be very similar to the development of Solar Sails which we will discuss later. An earthbound Space Elevator is frequently discussed as being able to reduce the cost for bringing a kg of payload up to space to as little as $10kg. However, building an earthbound space elevator is extremely challenging as with Solar Sails the biggest obstacle is the need to develop materials that are far more capable than those that currently exist- extremely strong but lightweight.

For an Earth-bound elevator, there has been talk about building the cable 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 or beyond. If supper strong but lightweight materials are developed and are able to withstand the rigors of space, then a earthbound space elevator maybe able to be built. The same materials would likely also 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. If seems possible that solar sails would become practical when space elevators become technologically possible- the material challenges are similar.

Besides material strength issues, there are many severe challenges to an earth-based space elevator. To sum up all the challenges:

- The tensile and mass requirements of a space elevator cable are far greater than any current material
- The earth has an extensive atmosphere that will attack the materials of the cable. These include moisture near the ground, and atomic oxygen at higher altitudes
- The earth has variable and unpredictable weather that will buffet the lower part of the elevator
- The earth has an extensive and intense radiation belt that will attack the cable material

- The earth has an extensive and intense radiation belt that must be traversed on voyages up and down the elevator so that any elevator will expose its cargo or passengers to a period of intense radiation
- The elevators themselves travel at a relatively slow speed. It will take days to reach geosynchronous orbit.
- The earth has ten's of thousands of satellites. Every one of these satellite orbits will eventually cross the cable. A space elevator will require essentially their to be no satellites or the cable will constantly need to be moved to avoid impacts

To fully appreciate the challenges of a space elevator, one only need to consider the length of the elevator cable and compare the strength of normal cable materials of steel.

One property of a material is called its specific strength. The specific strength is a material's strength (force per unit area at failure) divided by its density. It is also known as the strength-to-weight ratio or strength/weight ratio or strength-to-mass ratio. This can also be used to calculate breaking length, also known as the self support length which is the maximum length, of a fixed cross-section, that could be suspended and support its own weight.

$$L = \frac{\frac{T_s}{\rho}}{g}$$

Where:

$$L = Length$$

$$T_s = \ Tensile\ Strength$$

$$\rho = Density$$

$$g = gravity$$

The breaking strength of Steel ranges from Low Carbon Steel of about 4.73km to Maraging Steel of 29.7km. All of these are far shorter than required. There is a way of extending a steel cable further, and that is by making the top thicker and having it taper as it goes down.

Despite the impracticality of an Earth-bound space elevator, the advantages of space elevators are substantial and for planets or moons that do not have the high gravity and unique challenges of earth, they will likely be a key part of any future space infrastructure.

Almost all the moons and planets being considered for a space elevator are much simpler to build, and can be built with materials already available, including various materials like Kapton and M5. The tensile strength requirements drop off considerably as a planets/moon's gravity drops below the earths. The lower gravity means that the weight of the cable is much less, which in turn requires a thinner cable. Some prime candidates for the construction of a space elevator are:

	Dimensions	Comments
Moon		Can be build with current materials
Mars		Can be build with current materials
Ganymede		Can be build with current materials including steel
Callisto		Can be build with current materials including steel
Titan		Can be build with current materials
Ceres		Can be build with current materials including steel

Table 8-8

Specific strength refers to the materials strength (force per unit area at failure) divided by density. The formula is:

Equation 8-1 $L = \frac{T_s}{\rho} / g$

It is the self-support length under a gravitational force of g.

Space elevators from the Earth would be extremely challenging from an engineering and materials perspective. They are fare beyond current materials technology and are approaching the theoretical strengths of material. Furthermore since Space Elevators are fixed somewhere at the equator, all satellites will eventually collide with the tether unless actively maneuvered. Dead and abandoned satellites (and their debris) would have to be collected and removed from orbit. For these reasons I do not feel that a Space Elevator will ever be built around the Earth. However I could see them being built for the Moon (Chapter x), many asteroids, perhaps Mars (more on that in Chapter X) and some of the larger moons around Jupiter, Saturn, Uranus or Neptune.

Momentum Transfer

As with Solar Sails, a momentum transfer (MT) device can eliminate (or reduce) the need for fuel. Furthermore, from an engineering point of view, they are much easier to build. An MT has tremendous advantages and potential, especially for lower velocities applications- and for the foreseeable future will probably be the most practical technology for transferring large quantities of raw material through the solar system at relatively low cost.

Spin Launch is a company currently developing a unique system to cheaply and rapidly and cheaply launch payloads into space. They call their momentum transfer technology a Kinetic Launch System. As currently envisioned, a rapidly spinning composite arm some 45m long in a vacuum

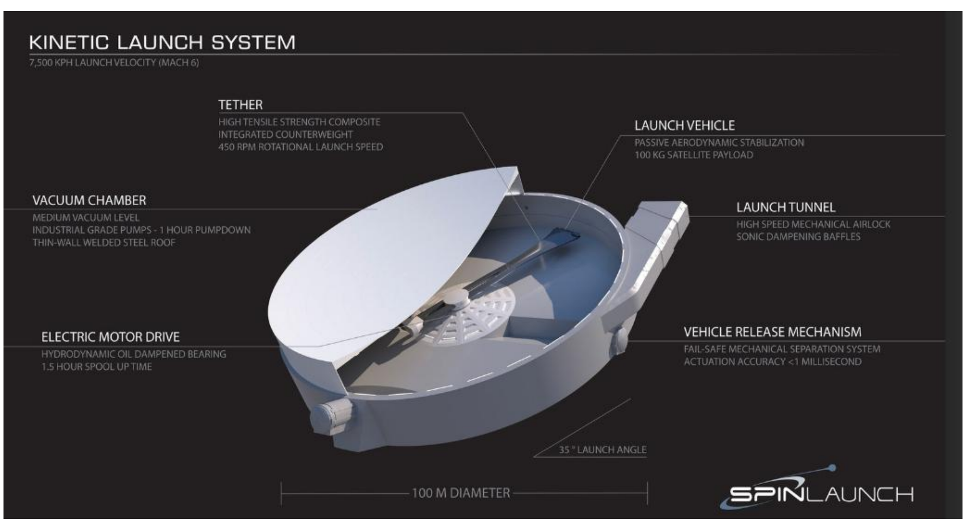


Figure 8-5 Spin Launch Kinetic Launch System (Launch, n.d.)

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 2.2kps. 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.

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 issue is whether or not we can build ones that are able to send payloads faster and, if desired, at lower gravitational acceleration so to be acceptable for human passengers. As opposed to some of the challenges of building a spin arm on Earth, the space based MT would not have to be concerned with the atmosphere, local gravity, and size- a very large radius MT could be built. An MT device could be designed to perform three different functions:

- Launch a payload. As with the Spin Launch Kinetic Launch Syster, an MT could launch from the surface of an asteroid or moon by gradually spinning a payload until it reaches its desired velocity, at which time it would be released.
- Redirection. A payload, launched either by another MT, or via traditional rocket propulsion, get hooked (as with aircraft performing carrier landings), be carried around and released at the appropriate time and direction- similar to a gravitational slingshot. In this case, no speed would be added relative to the MT device, just a redirection, but from the sun perspective an object would be able to perform a dV twice that of its approach velocity. For instance, a MT orbiting around the sun at 25kps and spinning at its rim at 3kps could be able to capture a payload traveling at anywhere from 22 to 28kps relative to the sun. Suppose a payload approached the spin arm at 3 kps, but at 28kps relative to the sun. If it was captured and redirected 180deg, it would now be traveling at 22kps.
- Acceleration or deceleration of payload. If the MT can either adjust its radius or change its rotational velocity, it could capture a payload for a longer period of time and either change its spin rate or radius to increase or decrease its velocity.

As an example, suppose we have a kilometer long MT that spins around a central hub with a payload at the end of the arm? If we spin it at 10 rpm the what would our velocity be?

EQUATION 8-2 $\boldsymbol{C = 2\pi r}$

$C = 2\pi(1{,}000) = \ 6283.1 meters$

Since we are doing 10 rpm the total distance traveled in on minute would be 62,831meters. 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.

$$\boldsymbol{I_{sp} = \frac{v_e}{g_o} = \frac{1047}{9.81} = 106.7 sec}$$

This would not be a very effective rocket.

What would be the acceleration force at the end of this arm? We can calculate:

EQUATION 8-3 $a_c = \frac{v^2}{r}$

$$a_c = \frac{1047^2}{1000} = \frac{109{,}662{,}784}{10000} = 1096mps = 111g$$

This is far too high for a crewed payload, but well within what electronics and a properly designed structure can tolerate. What is the gravitational limit for a payload and how fast can we spin? The Spin Launch system current concept calls for the rocket to experience 10,000g acceleration. By either lowering our "launch" speed or increasing our radius we can lower the g-forces felt by the payload.

The real limitation is the strength and mass density of our arm material- this will primarily determine what our performance can be.

We can figure out what our MT payload velocity is by taking the performance specifications of a variety of materials. 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.

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 8-4 $A_x = \frac{(\omega^2 m_p L)}{\sigma_{Allowable} - \omega^2 \rho \frac{L^2}{2}}$

For a given tip velocity we substitute:

$$\omega = \frac{v_{tip}}{L}$$

And get the equation:

Equation 8-5 $A_x = \frac{\left((\frac{v_{tip}{}^2}{L}) m_{payload} L \right)}{\sigma_{Allowable} - \frac{v_{tip}{}^2}{L} \rho \frac{L^2}{2}} = \frac{m_{payload}\left(\frac{v_{tip}^2}{L}\right)}{\sigma_{Allowable} - \rho \frac{v_{tip}^2}{2}}$

Where

$A_x = Area\ Cross\ Section\ at\ Location\ x$

$m_p = mass\ of\ payload$

$v = Velocity\ of\ Payload$

$\rho = Density$

$\sigma = Tensile\ Strength$

$L = length\ of\ arm$

A quick way of determining the maximum speed a particular material can handle is to assume only the weight of the arm material and to assume the arm has a constant cross section. In the equation 8-5 we can see that the denominator will go to zero (and hence the Area to infinity) when the allowable stress is equal to $\rho \frac{v_{tip}^2}{2}$. We can rearrange and use this equation to find the v_{max} tip speed.

$$v_{max} = \sqrt{\frac{2\sigma_{Allowable}}{\rho}}$$

This will give us the maximum tip speed with no payload. In reality this is a good starting point since the mass of the arm is usually much greater than the payload. If we adjust the allowable tensile strength to include a safety factor or margin then we can easily calculate max tip speeds for a constant diameter arm.

As an example lets select 7075 aluminum, factor in a 50% reduction for allowable stress to capture a safety factor, we will have the following:

$$\sigma_{Yield} = 572MPa$$

$$\sigma_{Allowable} = \frac{1}{2}\sigma_{Yield} = \frac{572MPA}{2} = 286MPa$$

$$\rho = 2810\ {}^{kg}/_{m^3}$$

Calculating we get:

$$v_{max} = \sqrt{\frac{2(286x10^6)}{2810}} = 451mps$$

We can try other materials for a higher performance. Plugging in a composite material with the following propertiest:

$\rho = Density = 1800kg/m^2$

$\sigma = Tensile\ Strength = 4.18GPa = 4.18x10^9Pa$

For this material we would get a maximum velocity of 1524mps- or over triple the amount for aluminum. If we use steel our number decreases since even though steel is much stronger (almost twice the strength of aluminum) it is almost three times heavier.

Material	Tensile strength used	Density	v_max (m/s)	v_max (km/h)
7075 aluminum (T6)	572 MPa	2810 kg/m³	451.7	1626
High tensile steel (1.0 GPa)	1000 MPa	7850 kg/m³	356.9	1285
High tensile steel (1.2 GPa)	1200 MPa	7850 kg/m³	391.0	1408
Composite	4180 MPa	1800 kg/m³	1524.0	5486

Table 8-9

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/m^2. (Yu, et al., 2000). With a material like this the momentum engine may be practical for extremely fast speeds. Assuming the same 1800kg/m3 density, but using 63GPa as the yield stress we get a maximum tip speed of 5916mps- or almost 6kps. However this would be assuming the strongest material that has ever been specified and would therefore be the upper limit.

These limits apply to an arm of any diameter or cross-sectional area and no payload. A tapered arm so that the hub has the largest cross-sectional area, and tapers linearly to the tip which has zero area, we have the following formula:

$$v_{max} = \sqrt{\frac{6\sigma_{Allowable}}{\rho}}$$

Using this we get a tip speed of 782m^2 for 7075 Aluminum.

In reality, we can get even more performance if we use a exponential taper- the arm grows faster than linear as we get closer to the hub. In this case we can use:

$$v_{tip} = \sqrt{(\frac{2\sigma_{Allow}}{\rho}} W(\frac{\rho L A_0}{2m_p}))$$

Note that the W represents a Lambert W function and is defined:

$$W(z) = \ln z - lnlnz + \frac{lnlnz}{lnz}$$

Where:

$$z = \frac{\rho L A_0}{2m_p}$$

With aluminum, and a very small payload mass of one kg, we get about 1543mps performance. The solutions is as follows:

$$z = \frac{\rho L A_0}{2m_p} = \frac{2810(1000)1}{2(1)}$$

$$W(z) = \ln z - ln ln z + \frac{ln ln z}{ln z} = 14.155 - 2.649 = 11.69$$

$$v_{tip} = \sqrt{(\frac{2(286x10^6)}{\rho 2810})11.69} = 1534\, mps$$

If we kept our Hub cross sectional area at 1m^2 and added a payload of 1000kg, we can have a tip velocity limit of about 1060mps. We can continue to increase the hub area but we have a rapidly diminishing rate of return so that a hub area with ten times greater will lead us to only a tip speed of 1240mps.

If we wanted to calculate the required diameter or the arm spinning a payload as well as calculate the stress at any point in the arm we would use the equation:

EQUATION 8-6 $\boldsymbol{A_X = m_p(\frac{v^2}{\sigma L})\exp(\frac{v^2\rho}{2\sigma}\left(1 - \frac{x^2}{l^2}\right))}$

Where

$A_x = Area\ Cross\ Section\ at\ Location\ x$

$m_p = mass\ of\ payload$

$v = Velocity\ of\ Payload$

$\rho = Density$

$\sigma_{Allowable} = Tensile\ Strength$

$L = length\ of\ arm$

$x = distance\ from\ hub$

The first part of our equation defines the Area at the tip and is:

$$A(l) = \frac{m_p v^2}{\sigma L}$$

Suppose we use our 7075 aluminum again and specify a 1m^2 hub cross section and calculate the max tip speed for a linear tapered arm.

:

$$\sigma_{Allowable} = 286MPa$$

$$\rho = 2700\ {}^{kg}/_{m^3}$$

$$L = 1000m$$

$$v_{tip} = 500$$

$$m_{Payload} = 1000kg$$

The first part, the Area of the tip comes out to 8.747x10^{-4} m^2

Calculating $\frac{v^2\rho}{2\sigma}$= **1.18**

$$A_{hub} = 8.74x10^{-4}\, e^{1.18} = \mathbf{2.84x10^{-3}m^2}$$

Tip speed (m/s)	Hub area (m²)
500	0.00285
600	0.00689
700	0.0173
800	0.0459
900	0.129
1000	0.392
1100	1.28
1200	4.51
1300	17.1
1400	71.0
1500	323
1600	1,600
1700	8,810
1800	52,600

Table 8-10

Calculating cross sectional area we come up with a very reasonable area with a diameter of about 6cm. If I raise the tip speed the area will naturally increase, slowly at first and then rapidly. In Table 8-10 and Figure 8-7 we can see that the diameter explodes as the material limits are reached. For aluminum, it is likely practical to build a device for launching payloads up to about 1-1.1kps, and perhaps a bit higher if we eat into our margins. In Figure 8-7 we show a typical graph for a composite that shows the rapid increase in hub area as tip speed increases. For composite materials we may be able to get as much a 5kps- though the amount of composite material for a 1000m arm would be substantial and all the material might have to be imported from earth.

For lower velocities the momentum transfer method provides a low tech and efficient way of transferring large amounts of mass- be it supplies or even spacecraft. Depending on the payload (humans, electronic, or raw materials) will determine the diameter needed- larger radius will reduce the g-forces experienced by the payload. For aluminum or steel, the performance is too low for launching payload from the moons surface (about 2.4-2.6kps is required- see Chapter 9) but may be adequate,

Figure 8-6

especially if supplemented by electric thrusters, from the asteroids. For a composite arm, the velocity limit is about is more than adequate to launch from the moon to L4/L5 for space station construction.

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 30GPa, and a density of 1800kg/m3 we could reach a tip speed of 13kps with a 1m2 hub area. The g forces would be 17552g which makes this impractical, but this can be offset by increasing our arm length. A 10km arm could increase our tip velocity to15.43kps, and would lower our g force to 2427g.

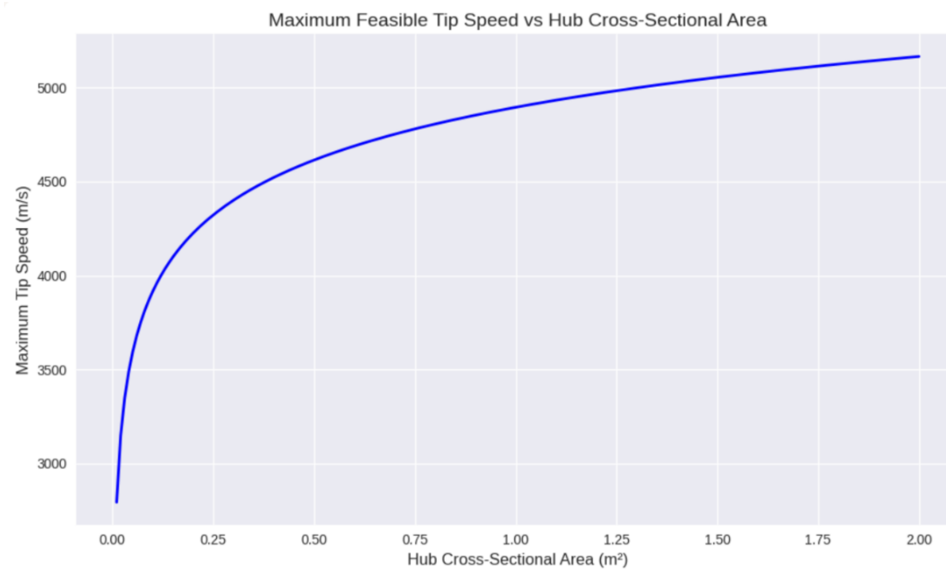


Figure 8-7 Graph of Tip Speed vs Hub Cross Section for Generic Composite Material

The momentum transfer arm of reasonable performance (2+kps) may not be feasible with normal metals. However composites, even of modest performance, make these MT devices very feasible except for the fact that the composite materials would need to be made in very large quantities and shipped into space. A 1000m arm will have a volume of about 707m^3, and would mass about 1.27x10^{6}kg. This would be about 1270mt, and require about 13 launches of 100mt each- and if placed on the moon about 6x more launches to provide the fuel allow the Starship to reach the moon. In addition, the motor and structure would need to be built (also possibly built on earth) and a counterweight of an equal amount (1270) would have to be mounted to keep the arm balanced- though this material would likely come from the moon.

A 10000m arm would have a volume of about 7930m3 and mass 1.43x10^{7}kg.

The momentum transfer arm with a modest 5kps performance would be an area of low risk from an engineering design and industrial perspective than a mass driver (see below). Nevertheless, the spin arm itself would still be massive. Furthermore, unless the arm was mounted to a very massive body like the moon or a large asteroid, it is desirable to have two spin arms. Spinning up a massive arm will use more energy than the actual energy of the payload and with a second arm or some sort of momentum storage device we will be able to recover the spinarms energy when we spin down in order to attach another payload.

If the body is relatively small (ie a small asteroid) we may want to have two spin arms to send payloads simultaneously in opposing directions to minimize our impulse to the asteroid, without which over time might cause the asteroid to change its rotation rate or even trajectory around the sun.

Alternative designs that mostly consist of cables in tension, may be more efficient for very large spin radii but would be better for redirect function rather than acceleration. We can use more common and cheaper materials than carbon laminate but the tensile strength of all other materials is far lower. Steel is typically in the range of 400-500MPa- or about 1/10th that of carbon laminate.

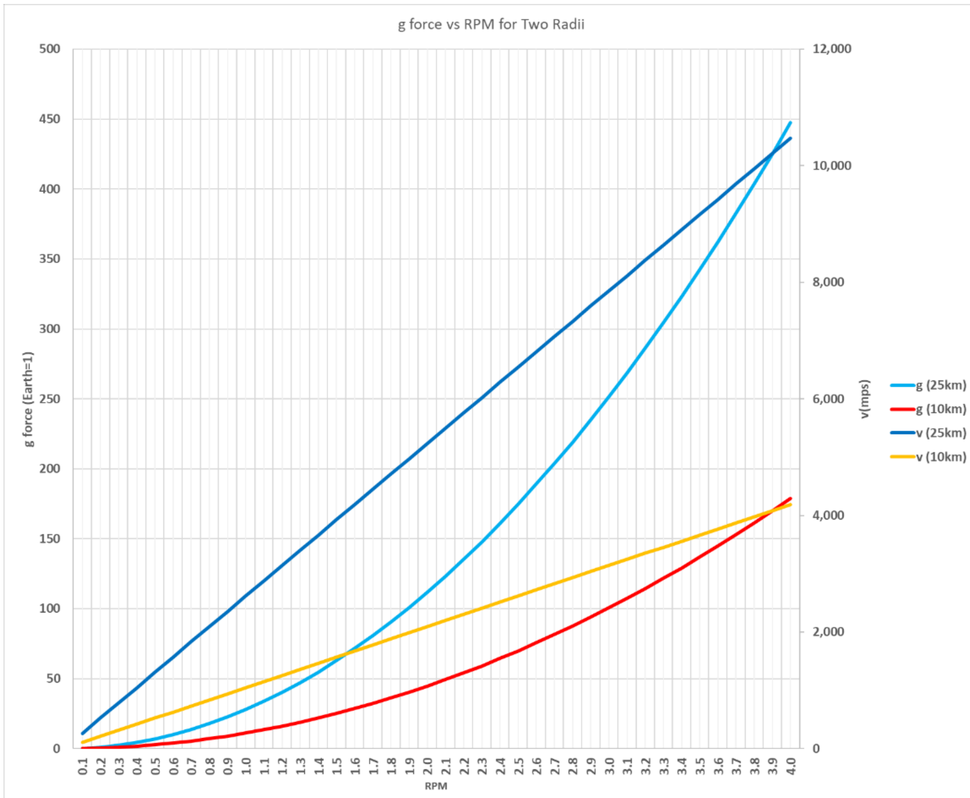


Figure 8-8

Depending on where we are launching from, for many interplanetary voyages a 3 to 6 kps MT may be more than enough performance for sending cargo to anywhere in the solar system. MTs seem ideal for launching high g tolerant payloads at relatively low velocities from low gravity planets and moons. To send large volumes at relatively slow speeds it is unlikely anything can match the spin launch performance. They are efficient, fairly simple in design, relatively compact (compared to the Mass Driver in the next section) and should have almost no operating cost except for the electricity consumed. For moving raw materials off of moons, Mars, and asteroids to various assembly or collection points, they will likely be the launcher of choice.

Unfortunately, unless an MT has an extremely large radius, they are unlikely to be useable for sending personnel through space. A passenger accelerated and released at 7kps from a 10km radius MT would experience 500g acceleration. To keep the acceleration down to 10g would restrict this MT to only 1kps launch speed.

One issue with the MT (as well as the MD) payload launching system is that once launched the payload will passively coast and depending on their capture location, will arrive at the target at a relatively high velocity- frequently several kps. A means of capturing and decelerating the payload will need to be developed. If the target is a planet or moon, it may be suitable to just impact into the surface or, if present, decelerate in the atmosphere. However, if the target is a space station or it is not desirable to impact the body at high speed, we might need to include a rocket to decelerate the payload on arrival- a not very efficient method. In Chapter 11 we look at standardized active cargo containers that can both perform modest trajectory modifications and will also permit being captured. A capture system (perhaps a net) or grappling device or cable will permit the cargo to be snared, but if the item is traveling at several kps this may not be practical. Our MT device can be a practical means of of both launching and capturing these payloads as long as their velocities are about the same as the end of the spin arm, and the rotational plane of the MT is aligned with the incoming payload. When a series of payloads are approaching the target, a grappling station and counter weight fixed around a massive hub would begin spinning around the station axis. The hub, if it is massive enough, will not substantially feel the mass applied. If it is less massive, then two symmetric grappling stations and hubs will need to be reeled out simultaneously but rotating in opposite directions.

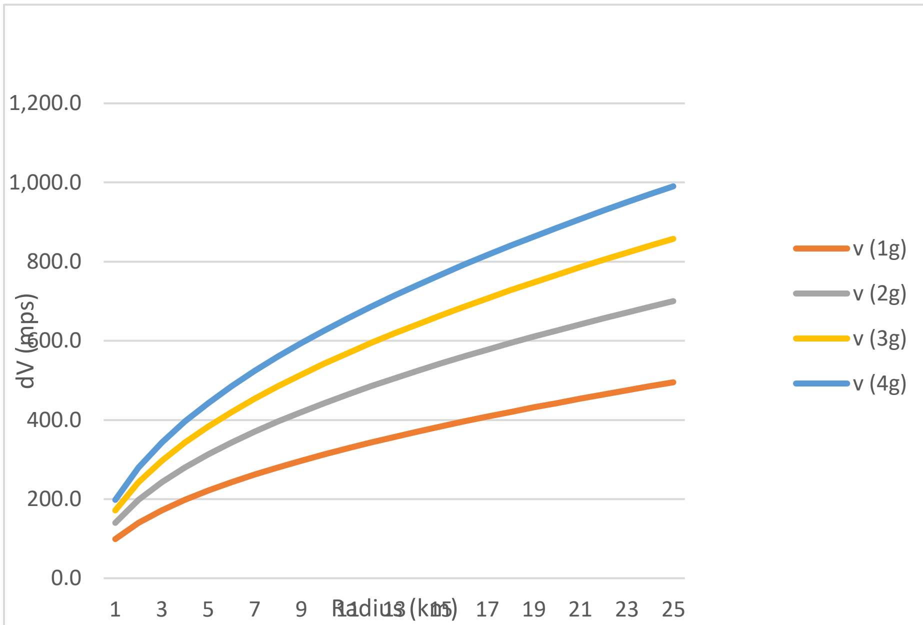


Figure 8-9

The size (radius) of the MT will be determined by the velocity of the incoming projectile, and the acceptable g force. A fast moving projectile will either need a rapidly rotating MT, with its associated high g force, or a slower MT but of much greater diameter. Figure 8-9 shows the relationship between RPM, perimeter velocity and g force experienced for two different radius MTs- 10km and 25km. This would be a low g capture with perhaps a human cargo. The Standardized Containers in Chapter 11 will be able to withstand 100g and perhaps higher, substantially reducing the arm size.

Note that the velocities at the end of a 10km arm spinning at 25 rpm is substantial but so is the g force- almost 7000gs. We will have the identical situation as with the MT launch station that wish to go very fast, no material will be strong enough to hold the mass of the capture station along with the weight of the cable or spin arm. Nevertheless, the MT capture system may be practical for capturing payloads traveling up to 6kps or so- though for these faster capture systems, g force will restrict the use of manned spacecraft.

Indeed, if we limit the g force to 1g, 2g, and 3 g, the velocities we get are shown in Figure 8-9. The assumption made is that humans can only tolerate about 2g, or if fit, 4g, for short periods of time.

As space industry grows we need to consider whether or not to use the MT devices scattered at several locations in the Solar System to add and subtract velocity for cargoes. We can imagine one at the Mars L5 location capturing a payload launched from an Earthlike orbit into a Hohmann transfer. Objects traveling in a Hohmann orbit will be a Perihelion and will be traveling slower than Mars. We can use the Martian atmosphere to aerobrake an object, this will only work for spaceships that have robust TPS. For those without a robust TPS, or cargo or payload destined for one of the Martian moons or an orbital station, an MT may be more practical. With it, an incoming payload would be swept up by the capture mechanism, swung around 180deg, and redirected toward Mars. Similarly, a payload from Mars headed for earth could be captured by a MT in front of Mars, reversed direction (speed lowered) and put into a Hohmann orbit towards earth.

Additionally MTs could be anchored to large asteroids at the L4 or L5 points. However, if the anchor point has a relatively low mass as with a small asteroid or an artificial space station, the forces to change the incoming payloads velocity or direction will impart a force on our anchor point, over time moving it. This may be counteracted by payloads going in the opposite direction, say taking a Hohman Transfer orbit back down to the inner solar system. The bottom line is that the MT, while a promising technology, is one that will have to be managed if used as a deep space transportation system.

Notionally I see MT's launching raw materials from the Moon, Asteroids and perhaps even Mars at up to 5kps for construction materials. Further into the future I see very large deep space MTs (perhaps anchored to very large space stations or Asteroids) with radius on the order of 300km, and rotating at about .08rpm. These would capture large, crewed ships and their payloads and expose them to about 2g force. If swinging the object on a 180deg trajectory they will cause a 5 kps dv.

Mass Drivers

Mass drivers, as with Momentum Transfer system, hold the potential to deliver at relatively low cost, vast resources anywhere in the Solar System. It has some of the advantages as a MT, as well as some disadvantages.

In essence, a mass driver is a linear motor. A detachable payload is mounted on an electromagnetic sled. The Sled is accelerated on a track to a specified velocity at which time the payload is detached to continue on its path, while the sled is decelerated and returned to its starting point to be reused.

The disadvantage of a mass driver is that they are usually many kilometers long and if placed on a planet or moon, they will only point in one direction. It also is more complicated in design as it will consist of thousands of electromagnets that will be electronically timed and will need to be precisely aligned. Furthermore, while the MT can build up its speed over a long period of time and accumulate a sizeable momentum, the MD will have to create this momentum rapidly over a few seconds during the acceleration phase. As with the MT, unless the payload also consists of its own rocket or electric thrust engines to modify its trajectory, once launched, it will only go in a fixed trajectory. Because of this, the receiving point will need some sort of means to capture the payload as it goes past.

Let us look at a sample Mass driver positioned on the Moon. Let us assume that it will launch a 100kg payload at 5kps. Furthermore let us assume that we can accelerate the payload at 100g. At 100g, you would reach 5kps in 5 seconds. Using the equation

Equation 8-7 $s = \frac{1}{2}at^2$

$s = \frac{1}{2}(1000)5^2$= 25,000m or 25km

Consider that we also need to decelerate our sled, so the total length of the mass driver will be around 50km. We would also have the added issue that over the mass drivers length, the moon would substantially curve away, so that if our mass driver started at ground level, it would be nearly 10km high at the end. Compare this to our notional MT from the prior section that had a 1km launch arm.

We could substantially reduce the length of our driver if we increased our acceleration, or if we did not need to reach as high of a velocity- both would be realistic.

For most of the raw materials to space stations being built at L5 we would probably use the moon. This tremendously simplifies the challenges as the launch velocity need be only a couple kps. In theory we could also launch to Mars. From the earth orbital distance, we need to add about 3kps to get to Mars. The moon orbits at about 1kps, so we would only need to add about 2kps to arrive at Mars.

How would a MT compare to a MD? Let's pick a target mass payload mass of 100kg, with a target velocity of 5kps. As calculated the MD would be about 25kilometeres if restricted to 100g.

To get to 5kps using a MT with a 1km in radius we would experience a very high 2500g.

Comparing Mass Driver with Momentum Transfer

Below in Table X-X we summarize the advantages, disadvantages of a Mass Driver over a Momentum Transfer.

	Mass Driver	Momentum Transfer
Materials Development	None; though superconductors are desirable	High tensile strength materials for above 2kps required
Technological and Engineering complexity		Easier and Cheaper
Payload Acceleration Stress	The Same	The Same
Directionality	Inflexible	X (Easier to point)
Velocity Flexibility	X (Equal)	X (Equal)
Absolute Velocity	0-20 kps	dV range limited to perhaps 0-5 kps with current materials
Energy Efficiency	X (Equal)	X (Equal)
Ability to Capture Cargo		Easier to position and synch with arriving cargo

Table 8-11

One area I can see where MT can be of substantial help is in reducing the dv required for many voyages. Suppose we have a target that does not have the ability to use aerobraking. However around this target (say an asteroid or moon of Jupiter) we have a large spinning MT. The MT would grapple the spacecraft as it went by, swing it around and release it in the opposite direction, subtracting all the velocity it would have needed to lose without expending any fuel. Because of their relatively compact size, MTs can also be manueverd to catch an incoming cargo- lining up their spinning arm and synchronizing its speed to snare the cargo's capture cable.

Both MTs and Mass Drivers, once the original capital outlay is complete, offer fantastically inexpensive ways to transport material across the solar system.

In chapter 11 we will look at the logistics of transporting large quantities of material throughout the Solar System. MTs and Mass Drivers are key. Both Mass Drivers and MTs will likely use some sort of standardized container, and in the case of Chapter 11 I looked at ones that are designed to handle 10g of acceleration. To keep a mass driver smaller, or reduce the arm length of a MT, we may need to build more robust containers to be able to handle 100g or 1000g, which will require a more robust, heavier container which would reduce some of the payload, but that would just be a tradeoff that would need to be analyzed.

Summary and Conclusions

Chemical rockets can propel a spacecraft to very high speeds, but compared to the size of the solar system, are severely limited… many objects outside of the orbit of Mars would take years of travel time to reach. The rocket equation limits the velocity of a spacecraft with a reasonable Mass Ratio of 20 to only about triple the exhaust velocity. To go faster a rocket will need a higher specific impulse.

Over the near and medium term- the next 75 years or so, the technologies that we will use for transportation are already ones that have been developed. The technologies will be refined and modified, but there likely will be no fundamentally new designs.

Most rockets for passenger transport will be Methalox, and a little further down the road, Hydrolox. Both will likely be used throughout the rest of the century. Transportation to Mars will be direct Hohmann transfer orbits for cargo, and after midcentury, Mars Cyclers for passengers.

In the next few decades, I can see limited application of Nuclear Thermal- perhaps for automated payloads and some limited manned missions to the Asteroid belt. If a manned mission is made to the Moons of Jupiter, it will likely require a nuclear rocket, unless a large Oberth maneuver is used around the sun. Until a large mining operation for nuclear fuel and nuclear fuel breeding industry is developed in space, most of the fuel will have to be brought up from earth at high cost which will severely limit its application.

Further out, two technologies hold tremendous potential for radically improving on our spacefaring civilization- practical fusion Power, and high strength materials.

Fusion power, further discussed in Chapter 8, if it can be made portable, will enable large amounts of energy for both powering Space Stations, as well as providing tremendously more capable rocket engines. A fusion rocket of sufficient capabilities makes interstellar transportation feasible.

Materials development is primarily in the area of building lightweight but extremely strong materials like carbon nanotubes. This will permit the construction of space Elevators, as well as other advanced devices including Momentum Transfer spin arms and Solar Sails (Chapter 6).

Chapter 9 - Space Stations

Large Space Stations

Of all the places that we will colonize in space, large scale space stations are the only ones that can provide an earth-like environment. Furthermore, from a resource, and technological perspective, they are as easy to build as a domed city and much easier to construct than a terraformed planet.

The advantages for a Space Station are considerable. They are:

- Scalable. Space stations can be constructed from relatively small housing a few people, to one's housing millions.
- Efficient in their use of resources. Even a large space station, massing several million metric tons, will require far less resources and energy than terraforming a planet or building a planet from scratch (Chapter X).
- Can be located anywhere, easing power and raw material requirements. A space station located in the inner solar system will be able to get its power from solar collectors. A space station can also be located near the source of its raw materials.
- Can have its environmental conditions tailored to human needs. Unless a world were constructed from scratch, most planets that can reasonably be considered for terraforming have low gravity. Only a space station (and the vastly more ambitious world building) can give an earthlike gravity.

It may be possible that sometime in the future humans can be genetically modified to function in zero or very low gravity… however this is speculative. Humans are at the end of a 3.5-billion-year chain of evolution that has exclusively occurred on the earth under earthlike conditions.

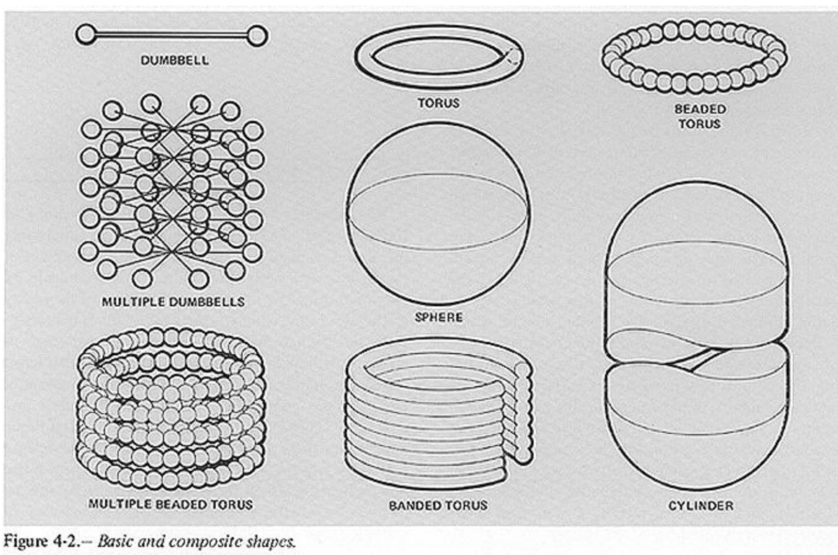


Figure 9-1 (Johnson & Holbrow, 1977, p. 41)

Fortunately, except for gravity, most other conditions on earth including oxygen levels, radiation levels and temperatures can vary within a range and it has been demonstrated that within this range humans can comfortably exist (see Chapter 4).

Figure X-X shows the basic space Station types. Space Stations are likely to assume one of four design configurations, each with its own benefits and drawbacks:

- Very small zero gravity modular stations (like the International Space Station (ISS))

- Small and Medium sized rotating Torus (up to 100,000 people)
- Small and Medium sized Sphere (up to 100,000 people)
- Large Cylinders (up to several million people)

For large Space Stations we would consider the Torus, Sphere and Cylinder. The purpose of the station will drive its location, the materials selected and its configuration and size. The need for stations to have radiation and meteoroid protection along with artificial gravity drives the requirement to make these structures extremely large. Adding the small but not negligent risk of meteoroid strikes, it will behoove us build them extremely robust. Due to this and the cost and difficulty of shipping large mass of materials the stations should be designed to last many decades but, especially for the larger station's centuries or millennia.

Design Parameters Based On Human Needs

I would see two separate and distinct types of stations… ones that orbit a planet or moon, and ones that orbit around the sun- usually a cycler or one of the L4, L5 stations. Cycler stations will have large surges of colonists or tourists that will arrive over a few days, stay for a duration of a few months (in the case of a Mars cycler) and then disembark at their destination. Initially I don't see any advantages to having any space station or space ship having an atmospheric pressure of more than 800mbar. Higher atmospheric pressure places greater stress on space station/spacecraft hull requiring stronger and heavier structures and will increase transition times for people donning and doffing a space suit. In Table 26 I have laid out the initial design parameters for some typical space stations. We will also need to provide radiation and meteoroid protection, gravity, suitable space for the inhabitants, recycling capabilities and adequate power. Initial baseline requirements would be along these lines:

Mission	Type	Population	Gravity	RPM	Atmospheric Pressure	Power Requirements Per Person	Comments
LEO, Geosynchronous Orbit	Stanford Torus	1000-250,000	.9g	1	800	2kWe pp	Likely to support Space based solar power and tourism
Large L4, L5 Colony	Stanford Torus	10,000-250,000	.9g	.5	800	2kWe pp	Earth/Moon Lagrangian points
Large L4, L5 Colony	Bernal Sphere/O'Neal Cylinder	100,000-5,000,000	.9g	.5	800	2kWe pp	Earth/Moon Lagrangian points
Lunar Elevator Anchor	Stanford Torus	1000-10,000	.65g	1	600	2kWe pp	Support tourism, embarkation for deep space missions
Mars Cyclers	Stanford Torus	1000-10,000	.65g	2	600	2kWe pp	
Mercury/Venus Cyclers	Stanford Torus	1000	.65g	2	600	2kWe pp	

Table 9-1

Addiitonal factors that need to be discussed Radiation and Meteoroid protection, sufficient space available per person (volume and surface (ground) area).

Meteoroid and Cosmic Ray Protection

Since the Meteoroid and Cosmic Ray protection is provided by the stationary outer hull which is disconnected from the inner, structural hull the thickness of the inhabited hull will be driven by the need to resist the internal atmospheric pressure, and the stress caused by the pseudo gravity. The outer hull which will provide cosmic ray protection and as described in Chapter 4 can be equated to 7 tons of material per square meter for water, and about twice that for normal rock or regolith. It may be possible, with the largest O'Neil cylinders (several kilometers in diameter), that the thickness of the station itself, combined a substantial floor and deep ground cover, supplemented by some active charged protection system, a large stationary hull may not be needed. However for most structures that will be built, including the cyclers, substantial passive shielding will be required.

For now, assuming we don't have active shielding, we will stick with the thickness' identified in Chapter 4, with 7mt water or 12mt regolith per m2.

With regards to the pressurized inner structure, here are some typical thickness of 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. We will look at hull thickness when we look at individual station designs.

Power

Power will come from either solar or nuclear fission – though fusion may be a source further into the future. However, until large space stations are built around Jupiter or more distant planets, the stations in Geosynchronous orbit, the Earth/Moon Lagrangian points and any cyclers to the inner solar system will be primarily Solar Powered. Mars Cyclers may have either nuclear or solar or both.

The amount of power needed will be determined by what the purpose of the station is and the number of colonists. A large self-sufficient space station that needs to grow it's own food will need about 10kw per person if it does not use sunlight for crop illumination. Per chapter 4, a good rule of thumb is that a fission nuclear plant will generate about 20We/kg- especially for large, non-moving space stations. Therefore a 1MWe powerplant will mass 50,000kg or 50mt. Note a lot of this mass will likely be for heat dissipation- it will generate 3MWt of heat that will need to be radiated. For a 10,000 person colony, this would mean 1 GWe power plant which will mass a substantial 50,000mt.

As we saw when developing our Uber Spaceship in Chapter 8, this mass per watt generated is a large penalty for Spaceships that have to move throughout the Solar System where every kg of mass reduces the capability of the ship. For this reason, an optimum design should be developed that generates 40W/kg so this should be an area of aggressive R&D and this is what we used in Chapter 8. However for a large and permanent space station this will not be an issue.

If the Space Station is located at an Earthlike distance or closer, food can be grown mostly under natural daylight where sunlight is reflected into the space station growing areas. In this case we could reduce our power requirements per person to only 2kW$_e$ and a 10,000 person colony would require only 200,000kWe and mass only 10,000mt.

Many large stations, including those at Earth Lagrangian points and low earth orbit, will probably use Solar Power instead of nuclear. As mentioned in Chapter 4, the most high tech design used for the Juno spacecraft generates about 35W/kg for solar cells at 1 au. A 1 GWe power plant would weigh 28,571mt.

What would the habitable volume be for a space station or interplanetary spacecraft?

People need space if they are going to live permanently or for extended periods of time. For psychological effects, the need for privacy and the need to have low sound levels for sleeping, all drive constraints for volume. Traditionally space has been for the very elite and selective population with extensive training

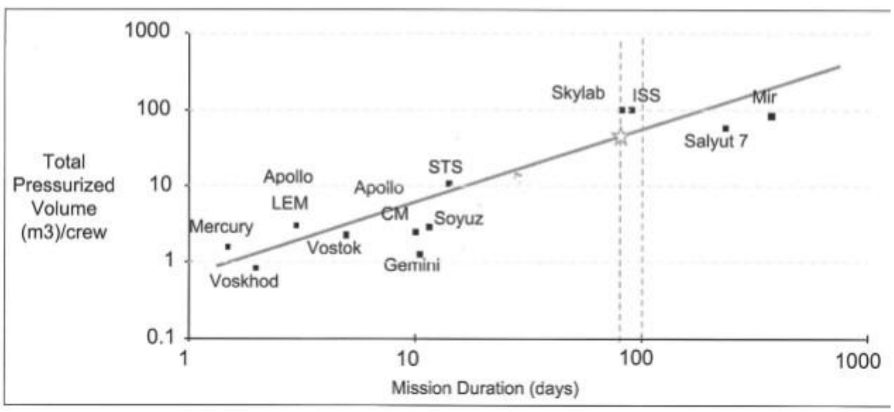


Figure 9-2 Pressurized Volume vs Mission Duration

Figure 9-2 shows the historical progression of volume per crew member vs mission duration. 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 m^3 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 m^3 per person. The SpaceX Starship is planned to have a 1000m3 volume which depending on the amount of people, can support 10 people at 100m3 or 100 people at 10 m3.

A 100m3 size is probably the minimum that we would like to use for a large and permanently manned space station- and the graph above seems to suggest a number closer to 500m^3/person. A tiered approach is warranted, for missions of a couple of days (ie launch from Earth to LEO or LEO to the Moon) 10m^3 is warranted. For voyages a little longer- up to a couple of weeks, 20 m^3 is acceptable. For missions or continuous occupation of up to six months (ie Mars Cyclers, small space stations that don't grow their food), 50 m^3 is probably acceptable. Finally, for permanent habitations or voyages of several years, 100 to 500m^3 would be appropriate. One shortcoming of this analysis is that all prior spacecraft have been zero gravity- so volume has been the primary determinant for how much space people have. In reality, most future space stations and some spacecraft will have artificial gravity which means not only volume but floorspace becomes important. How much floor space is adequate for long term habitation? 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 space station or large spaceship 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) (approximately 40.5 m^2 per person) and perhaps much less. 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?

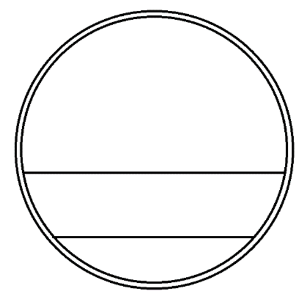


Figure 9-3 Possible Torus barrel Cross Section With 2 Decks

The 40.5 m2 baseline may be overly pessimistic. There are many high density aggressive growing techniques including hydroponics, genetically engineered plants (including algae) and the option for 24 hour sunlight in many space stations. In addition, the atmosphere can be adjusted to have slightly more CO^2 which aids in plant growth. For our baseline colonies 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 we would only need 20.25 m2 per colonist. Keeping in mind that we will also need land for housing and manufacturing on the larger space stations 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 27 m^2pp.

Note that frequently our structures, whether a torus, or cylinder, can have multiple floors and even buildings. We could have two levels with crops grown on both as per Figure 12-7.

Regardless, if we were to design a large, permanently occupied space station, a volume of 500m3 with a floor area of 30m2 (rounding up) should be a reasonable target.

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 9-1** $t_m = \frac{p_o r}{\sigma_w}$

Hoop Stress **Equation 9-2** $t_h = \frac{\left(\frac{p_o}{2}\right)\left(\frac{r}{R}\right)+\left(\frac{p_g}{\pi}\right)}{(\sigma_w - \rho R)} R$

Where $p_o = atmospheric\ pressure\ of\ torus$

$p_g = equivalent\ pressure\ of\ psuedogravity$

$\rho = density\ of\ structural\ material$

$R = major\ radius$

$r = minor\ radius$

$\sigma_w = working\ stress$

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.

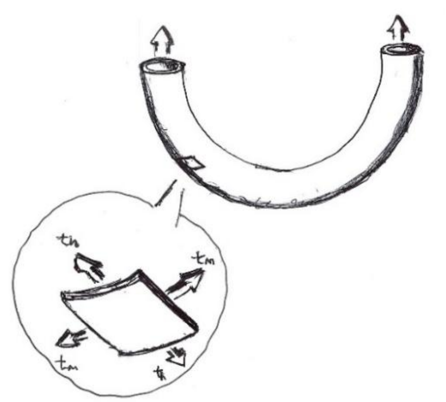


Figure 9-4 Meridional and Hoop Stress

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 $p_o = \frac{1}{2} earth\ normal$, 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 m^2.

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 space stations will come in a variety of sizes, shapes and purposes.

For us to calculate the hoop stress in our space station we need to know the internal mass. This is a little tricky since we need to make some assumptions. If we are growing most of our food, this will require a large area. Furthermore we need to have space for small buildings, people and trees.

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. It also shows that the structure with the thinnest shell for any particular radius is the Torus, with a cylinder configuration requiring the thickest shell. This chart gives a representative internal deadload pressure of 5.1kPa. This works out to 5100 nt per square meter. A 1-meter-thick layer of water would exert a 10,000 nt per square meter- or twice the calculated load. In this example, the ½ atmospheric pressure provides ten times the stress of the deadload so atmospheric pressure is the predominant stress, which explains why the team went with a proposed internal atmospheric pressure of only 500 mbar. We can increase the deadload by increasing the shell thickness, decreasing the atmospheric pressure, or decreasing the gravity.

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.

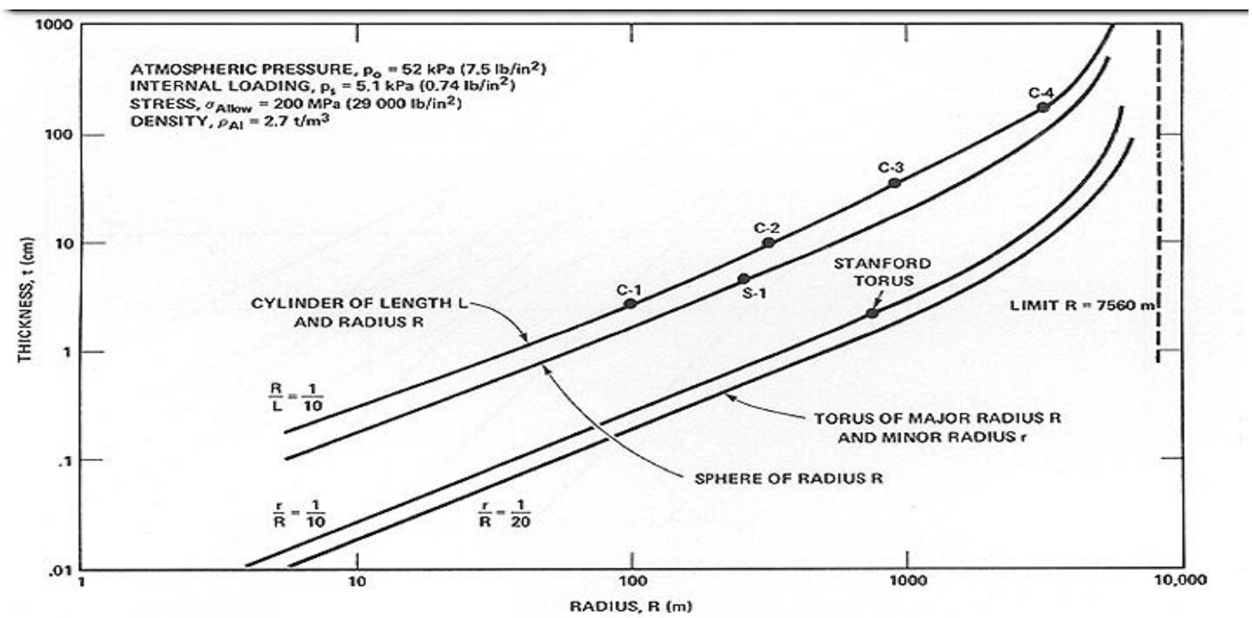


Figure 4-3.— *Shell thickness as a function of radius for spheres, cylinders, and toruses spinning to produce 1 g.*

FIGURE 9-5 SHELL WALL THICKNESS FOR VARIOUS SIZE SPHERES, CYLINDER AND TORUS'S (Johnson & Holbrow, 1977, p. 42)

The space stations can be made of many materials, the most likely being Aluminum, Steel, or Titanium. For the Space Studies Team, they picked aluminum which 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 repeating cycles of stress and strain (referred to as the fatigue limit)- 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. However, because of these issues, along with our desire to make these structures permanent (last for hundreds of years) I believe that steel may ultimately be the material of choice. While heavier, and susceptible to corrosion, it is somewhat stronger and does not have a fatigue limit. Furthermore, when the Space Studies team was creating its recommendations, the risk of cosmic rays was identified but probably underappreciated. In the ensuing half century the amount of passive protection that is needed has been increased. Combined with the likely several centuries that a station will be occupied, I believe the structures will likely be more robust and heavily constructed. Indeed, all things being equal, switching to steel will nearly triple the structures mass.

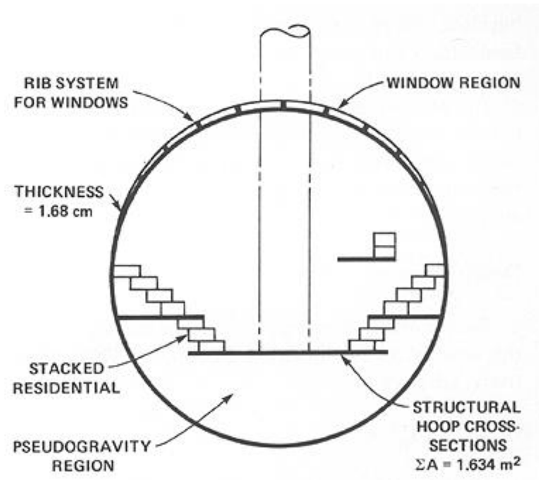


Figure 9-6 Stanford Torus Cross Section

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). To effectively choose the best material, additional cost benefit analysis and structural analysis will have to be done.

Size of Station

With a population of 10,000 people and the requirement to average 500m^3 of volume per person, we will need a station with a volume of 50million m^3.

We also want a gravity of .9 at .5rpm. This equates to a station with its outside rotational diameter of 6400m. For a torus shaped structure, with a Major Radius of 3200m to get our station volume of 50 million m3 we need to calculate the minor radius. We can use the formula:

Equation 9-3 $r = \sqrt{\frac{V}{2\pi^2 R}}$

Substituting we get a minor radius of 28m. Rounding to 30m we can calculate the floor volume by assuming we had a single floor centered on the torus hoop, it would be 60m wide, and stretch for the circumference, or 20,106 meters (20.1 km), a sizeable structure indeed. This would provide 1.2 million m^2 of floor space. This is a little less than half our target so it implies we will have at least two levels.

Bernal Sphere

A Bernal Sphere is perhaps the most logical and simplest design- a spinning pressurized sphere. Structurally it is mass efficient for the volume enclosed. However its biggest flaw is the floor area. Only a small band around the "Equator" will have normal gravity, while the sides both will slope steeply and have lower gravity. At a point half way up the wall the floor will slope at 45deg, and the gravity will be only about 71% of that at the equatorial base.

Materially the most efficient design would be a stressed shell, where the thin shell will take the loads. There are three primary components to loading, in the general order of highest to lowest: the stress caused by the internal atmospheric pressure, the stress caused by spinning of the sphere to create the artificial gravity, and the non-structural areal mass which would be the internal mass of any buildings, equipment, ground cover/soil etc. This areal load can be evenly distributed but most likely will primarily exist at the equator- where the habitations, buildings, parks and croplands are.

Equation 9-4 $\boldsymbol{\sigma_p = \frac{pr}{2t}}$

Where:

$$\sigma_p = Stress\ caused\ by\ internal\ pressure$$

$$p = internal\ pressure\ (Pascals)$$

$$r = radius\ (meters)$$

$$t = thickness\ (meters)$$

And

Equation 9-5 $\boldsymbol{\sigma_\omega = C\rho_s\omega^2r^2}$

$$\sigma_\omega = Stress\ caused\ by\ centrifugal\ rotation\ forces\ from\ shell\ density$$

$$\omega = spin\ rate = \sqrt{\frac{a_{acceleration}}{r}}$$

And the addition of the two would give you your total stress.

Equation 9-6 $\boldsymbol{\sigma_{tot} = \sigma_p + \sigma_\omega = \frac{pr}{2t} + C\rho_s\omega^2r^2}$

The factor of C is more complicated to derive, however it is there to capture the areal load, and if there is no internal, nonstructural mass or this mass is supported separately, C=1. We can carry the areal nonstructural load separately from the spherical structure- the sphere would carry the stress of its spinning structure as well as the internal atmospheric pressure, but have nested within it a cylinder which will carry the nonstructural mass (buildings, farm land, etc). An equatorial belt of perhaps a meter deep of topsoil (or structure) might be only 20% or 30% of the Bernal Sphere diameter.

The basic formula is good for determining the rough diameter of a sphere of a particular material and material thickness. The main stress on the sphere is primarily σ_p internal atmospheric pressure which if 80kPa is equivalent to almost 3 meters of top soil- which is far more than would normally be needed for the areal load.

Rearranging terms, if we select a radius and material we can come up with the required thickness.

Equation 9-7 $\boldsymbol{t = \left(\frac{\frac{p_o}{2}+p_g}{\sigma_{allow}-\rho_s r}\right) r}$

Alternatively, if we have a material and the internal stress, we can calculate the radius:

Equation 9-8 $\boldsymbol{r = \frac{\sigma_{allow}}{\frac{p}{2t}+\rho_s a}}$

With

$$a = acceleration\ of\ gravity\ in\ m/s^2$$

Plugging in:

$$\sigma_{allow} = 250MPa = 250x10^6 Pa$$

$$\rho_s = 7850kg/m^3$$

$$p = 80{,}000Pa$$

$$t = 20\ cm = .2m$$

$$a = .9g = 8.829\ m/s^2$$

This comes out to an allowable radius of about 121m, or a diameter of about 240m. In practice we may have to reduce this if the shell is carrying the internal load of nonstructural mass at the equator, but this is a good first approximation of the size of an allowable sphere with a shell thickness of 20cm. Note that by doubling the shell thickness we almost double the allowable diameter- but not quite. A 40cm thick shell would have a radius of about 467m and a 1meter thick shell we could have a diameter of 1065m. Eventually you reach a diameter too large for the material to handle its own spinning mass.

Thickness (m)	Radius (m)
0.10	61.5
0.20	120.8
0.30	178.2
0.40	233.8
0.50	287.7
0.60	339.6
0.70	390.1
0.80	439.3
0.90	486.6
1.00	532.7
1.10	577.5
1.20	620.8
1.30	663.1
1.40	704.1
1.50	744.2
1.60	783.0
1.70	820.4
1.80	857.1
1.90	893.3
2.00	929.0

Table 9-2

As our thickness increases, our pressure term $\frac{p}{2t}$goes to zero and the load is driven by the rotational mass of the structure alone. Carried to an absurd extreme, this can be calculated by:

Equation 9-9 $r_{max} = \frac{\sigma_{allow}}{\rho_s a}$

We would max out as a solid sphere of spinning steel with a radius of about 3606m or 7212m diameter. For Aluminum, with a lower density, we would max out at a radius of 8390m or a diameter of 16780m.

Finally, to address the flaw of Bernal Spheres where only the equator floor would be perpendicular to the centripetal force, we would probably have a false load bearing floor that would be a nested cylinder with about 30% of the spheres diameter. Gravity would be consistent at this load bearing floor but would be reduced to about 82% of the force at the spheres equator.

Stanford Torus

The Stanford Torus, is as explicit in the name, a large Torus. It has the name “Stanford” as the original concept was developed in detail by a team of Stanford students and professors. As with the Bernal Sphere, the Stanford torus design both will spin to provide gravity, and will be pressurized for habitation. The Stress can be calculated by:

$$\sigma_{Total} \sim \frac{pR}{2t} + \frac{\rho\omega^2 R^2}{3}$$

To calculate the skin thickness required of a particular structural material we would use:

$$t = \frac{pR}{2(\sigma_a - \frac{1}{2}\rho\omega^2 R^2)}$$

Meridional Stress

Equation 9-10 $t_m = \frac{p_o r}{\sigma_w}$

Or if we rearrange the terms:

Equation 9-11 $\sigma_{meridional} = \frac{pR}{t}$

Hoop Stress

Grok says $\sigma_{hoop} = \frac{(P+P_g)R_{eff}}{t}$

Equation 9-12 $t_h = \frac{\left(\frac{p_o}{2}\right)\left(\frac{r}{R}\right)+\left(\frac{p_g}{\pi}\right)}{(\sigma_w - \rho R)} R$

Total Stress

O'Neill Cylinder

$$\sigma_{vm} \approx \sqrt{\sigma_\theta^2 - \sigma_\theta \sigma_z + \sigma_z^2}.$$

Where hoop membrane stress is:

$$\sigma_\theta = \frac{p\,r}{t} + \frac{\rho\,\omega^2 r^2}{2}$$

And axial stress is:

$$\sigma_z = \frac{p\,r}{2t} + \sigma_{z,\omega}$$

Hoop stress is frequently much more significant. To calculate for material thickness we come up with:

$$t = \frac{p\,r}{\sigma_a - \frac{1}{2}\rho\omega^2 r^2}$$

$$t = \left(\frac{p_o + p_g}{\sigma_w - \rho R}\right) R$$

Calculating Mass of a Space Station

The mass of the Space Station primarily consists of the following elements:

- Habitation Structure- including station floor deadload, atmosphere, living space
- Power plant(s) including cooling radiators if needed
- Radiation Protection

To calculate a space stations mass, we must begin by deciding the size of the habitation module, how many people it needs to support, and the environmental conditions that will be provided (primarily gravity). Once this is identified, we can go on to calculate the power requirements, and the mass of the radiation protection. The size and varieties of structures are endless, so lets just do a sample using the parameters we have developed.

Torus:

When originally looking at possible future markets for Space that could directly aid in the development of a Space Society, we considered visits to both LEO and L4/L5. One thing that should become obvious that the economies of scale and the engineering involved mean that either we go very small- small space stations with no gravity and perhaps a dozen travelers, or we go large with a full blown, and more comfortable, rotating station. The requirements for large diameter, as well as the likelihood that durations will be longer, and for some people permancent, also drives the need for greater radiation protection, especially is we go to L4/L5 where the earth and its magnetic field will offer much less protection.

For this reason, along with the fact that this book is about colonization, I will focus on a mid-sized Stanford Torus like structure that will serve to house 10000 colonists and tourists. This is about 1000x more than currently live on the ISS, but is only 1/10th the size of the originally planned Stanford Torus. The requiment will also be for a majority of the water and food to be reused and recycled.

The size of the Torus is driven primarily by the target population, but also the desired gravity and rotation rate. To minimize the Coriolis effects and maximize comfort, the slower the rotation rate Is preferred- ideally .5rpm or slower. But this leads to a truly massive station. If we use our target gravity of .9g (8.83mps2) the diameter would be 3.2km. While structurally this is possible, it is such a leap from current capabilities that this will likely be done after several smaller stations were built. The initial mid-size stations will likely be funded to a large extent by tourism and a 3.2km station might be too large for the amount of tourists visiting, and the revenue they will generate. To compromise, if we target 1rpm, our station would now be 1.6km in diameter- still large but much more ac some Let us choose a moderate size torus station with the following characteristics:

Parameter	Specification	
Population	10,000	
Gravity	.9g (8.83 mps^2)	
Rotation Rate	.5rpm	
Radium/Diameter	3220/6440 meters	
Volume	$500m^3$ per person	5 million m^3
Floor Area	$27m^2$ per person	2.7 $million^2$
Atmospheric Pressure	80% (or 800mbar)	Oxygen/Nitrogen at 25/75% mix
Radiation Levels	200	
Power requirements	2 kWe pp (Sunlight); 10kWe (LED)	Power supplied via Solar; 20 MWe (if using sunlight) 100,000 MWe (for Artificial Lighting)

Table 9-3 Torus at Geosynchronus Orbit or L4/L5

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/m3 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/m3 (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:

Mass of Atmosphere

Extraordinarily Large Space Stations- Ring Worlds

The strengths of normal materials restrict the diameter and size of truly large space stations as can be seen in Figure 9-5, where for aluminum the absolute limit for a radius is about 7.5km but this would involve a skin that were infinitely thick. If we keep our shell thickness to a more realistic thickness of under half a meter, then torus of about 5km in diameter could be built (though the minor radius would have some influence on this) . We could build a larger station but this would involve some changes in our parameters:

- Reduce internal atmospheric pressure
- Reduce Gravity
- Using Stronger but lighter materials (ie Composites)
- Using a different design

One design change that could be made would be to separate the pressure vessel from the rotating station. This has been looked at (Ruzicka, 2024). One of the advantages of decoupling is that the external pressure vessel, since it no longer needs to be rotated, can be made almost infinitely thick. In an example, the authors proposed an outside pressure vessel 9726 kilometers in diameter composed of 734m thick Stainless Steel (Ruzicka, 2024, p. 6). One complexity of this design is that the rotating structure is now spinning rapidly within a pressure vessel. Air resistance (not to mention the sound associated with a rapidly spinning vessel), will cause frictional drag and the tendency to couple the stationary shell with the rotating habitat. These need to be addressed in the design.

As previously discussed, there are limitations on and disadvantages to extremely low pressures… about 1/3 atmosphere pressure with almost pure oxygen is likely the limit and this limit comes with extreme disadvantages of comfort, sound transmission, and fire risk. For various reasons I settled on 800mbar of pressure as the best compromise, with few disadvantages and several structural benefits. However we may push this to an atmosphere of 500mbar with a 50/50 mixture of nitrogen and oxygen.

Reduced Gravity is viable and likely acceptable, but again there are limits. This is an area of even less experimental knowledge and experience. I somewhat arbitrarily set a gravity at 90% earth normal as a conservative value, but experience may demonstrate that we can go much lower… perhaps down to a Mars gravity of 1/3 earth normal. Without actual data, likely not available for several more decades, I would stick with the .9g to be on the safe side.

Stronger and lighter materials are available, but likely impractical in the quantities required over the next century or so. Most lightweight materials are carbon based and need to be manufactured. Furthermore, Carbon is spread throughout the solar system but not evenly spaced- the moon for example has hardly any. The shear amount of carbon needed, the energy required and the scope of manufacturing to build very large space stations make this solution impractical for the short and medium term.

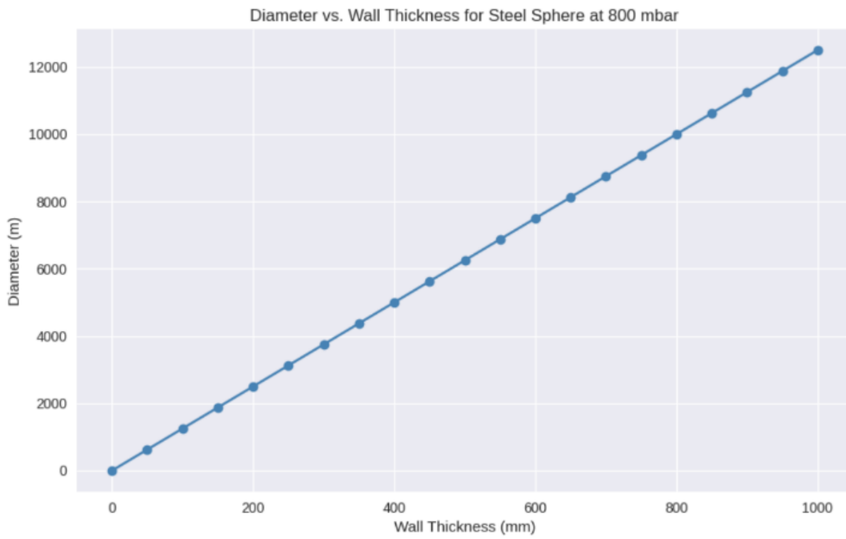


Table 9-4

Can we pick a different design style that permits a larger structure? There are. I will call this a ring world, but in effect it will be a torus with the added design choice in that the torus is also supported by cables radiating from a central hub. The center of the hub would likely be a small moon or asteroid and would have been the source of most of the materials used to build our ring.

What would such a ring look like? As proposed in our original space station- we will have a gravity of .9g, and an atmospheric pressure of 800mbar. However, we would substantially increase our radius over our other stations and thus reduce our rotation rate. Ideally, for our notional ringworld, we would want a rotation rate of once every 24 hours. This works out to a rotational rate of only $7.2722x10^{-5}$ radians/sec. Unfortunately, at this leisurely rotation rate, you would have to be 170,000km from the center to experience .9g. We would encounter the same problem as that of the space elevator- our normal materials are just not strong enough to stretch 170,000 km- their own mass would create so much stress that they would immediately fail.

Using a thin wall formula for a torus, and assuming we have a network of cables from a hub that supports the dead load, below are some possible diameters

Minor Radius	Major Radius	
1000	2125	
500	2625	
250	3000	
100	3075	

If we abandon the idea of a 340,000km ring that rotates once every 24 hours, what size ring could be reasonably be built? If we settle on a rotation rate of 4 times per day (once every 6 hours), our numbers

Formula:

$$R = \frac{2\,t\,\sigma_{\text{lim}}}{p} - a$$

Given:

- **t = 0.5 m**
- **σ_lim = 250 MPa**
- **p = 0.08 MPa**
- **minor diameter = 100 m ⇒ a = 50 m**

Compute prefactor:

$$\frac{2 \cdot 0.5 \cdot 250}{0.08} = \frac{250}{0.08} = 3125 \text{ m}$$

Subtract minor radius:

$$R = 3125 - 50 = 3075 \text{ m}$$

Result

- **Allowable major radius R = 3075 m**
- **Center-to-center diameter = 2R = 6150 m**

become much smaller- a diameter of "only" about 22000 km is needed. This is still on the high side, requiring large taper ratios for normal steel or aluminum, but it is getting much more feasible. A rotation rate of 8x per day, or once every 3 hours, is probably doable… the diameter of such a ring would be 5300 km in diameter.

There are many advantages to building such a large structure. The shear size of this structure, when combined with active cosmic ray protection, will eliminate the need for passive protection.

Chapter 10 - Cities and Colonies

The building of a permanent human presence depends on systematically building capabilities, both technological and infrastructure.

Cities

Cities, by definition, have large populations. On essentially airless bodies like the moon or Mars, it would be impractical to have thousands of small, pressurized homes and factories tied together via pressurized tubes. More practical is building large, pressurized superstructures and having “normal” houses built within. Since this large structure is pressurized, many of the same configurations and considerations for a large space station apply. One difference between them would be that the space stations need to spin to provide artificial gravity, while the pressurized cities will be stationary and built to withstand the planet’s gravity.

Using the same logic as for a pressurized Bernal space station, the ideal configuration to minimize shell material, would be a large sphere. Such a sphere would be considered a thin- walled structure and the stress be calculated using formula 9-4:

$$\sigma = \frac{pr}{2t}$$

Where:

σ= stress

P= pressure in Pascals

r= radius of sphere

t= shell thickness in meters

This could be placed within a crater of appropriate size. However, on a planetary surface a sphere would not be an ideal structure to inhabit. A sphere would be deformed in a gravity environment, it would also not be easy or practical to build- extensive scaffolding would be needed until pressure were introduced and the structure could inflate. The bottom area would be very small and land as well as buildings would have to be built on terraces and the top half would be just a large empty space. To give a more practical flat and large living surface, we would fill the bottom half of our distorted sphere with dirt up to the halfway point and then build and live above this. However, this is an inefficient use of materials- a large sphere might have hundreds of meters of fill in the bottom half. More practical would be a portion of the sphere- such as a dome. However, the issue with the dome is that the upward force will be extremely large and the circumference of the dome would have to be deeply anchored into the planet. The bottom of the dome could be a large plate but the shear stress would be to large for anything but the smallest dome. We can design around this with all of the following:

- Curved base to transmit the shear loads
- Anchored perimeter
- Filling dirt/regolith on top of the dome

The last items is required anyway- as with a space station, there is a need for radiation protection. A structure built on an airless world will have approximately half the radiation exposure that a free-floating space station would encounter since no cosmic radiation will enter the structure from below. However, this radiation level is still far too high for long term human habitation so a similar solution as was used with a space station will need to be applied… the top of dome will need to be covered with either ice water or regolith. As opposed to a space station where the insulating layer is separated from the spinning station by a narrow gap, on a planet or moon the insulating layer can directly lay on top of the dome. If the weight of the regolith layer were to be exactly the same as the atmospheric pressure below it essentially means that the dome can be infinite in size.

If we used our notional standard atmospheric pressure of 800mbar, and wanted to exactly counteract the force of atmospheric pressure we would need to have 8155kg m^2 of rock on top at earth gravity- or about 49,000kg m^2 at lunar gravity! For the moon, this works out to about 16m deep layer of dirt covering our dome. This is far in excess of the needs for radiation protection and even most meteor strikes (see Chapter 4). If we opt to go with a lower 600mbar pressure, this will of course reduce our regolith top cover, but even this will be more than sufficient for radiation and meteor strikes.

On the moon and Mars, it appears that initially we will have a large supply of stainless steel. Musk has proposed that a million tons of mass will need to be moved to Mars. While the Starship is still a design in progress, and its performance will change over time, indications are that Musk believes the V3 version will carry 200mt of cargo. This implies 5000 SpaceX Starships will land on Mars. While it is likely that some of these ships will be refueled on Mars and return to Earth, most will likely stay behind. Let's assume that 4000 space ships stay behind. With a height of 400m and diameter of 9m each ship has a surface area of 11,437 m^2 of 4mm thick Stainless Steel. This means that we have 45,748,000m^2 of stainless steel. If this was put into a spherical city, the city would have a diameter of about 4.8km- sizeable indeed and easily able to hold several hundred thousand colonists. In addition, by adding the regolith on top, the city can assume a much flatter profile, more dome like with a flat base, and be considerably larger. Regardless, for the initial cities on Mars and the Moon, using the abandoned SpaceX starships will likely serve as a source of Stainless Steel for building a large city. How could such a city be constructed? If we wanted to calculate the allowable size of a pressurized sphere we would talk our Formula 9-4 and rearrange the terms to get:

$$r = \frac{2t\sigma_{allowable}}{p}$$

Plugging ins some reasonable factors of :

σ_{Yield}= 205MPa

$\sigma_{allowable}$= 50% or 102.5MPa

p= 800mbar or 80000Pa

t= .004m

Solving we get a radius of only 10.25m. However, on top of this dome we will need to add several meters of Martian regolith for radiation protection. If we load the top of the sphere with the equivalent of about 12,000 kg m2 of rock (about 3 m^2) this would effectively reduce the pressure difference from the outside to the inside down to only 100mbar we get a radius of about 82m- enough for a modest sized colony.

At least for the initial colonies, ease of construction will be a top requirement. We will not be able to make stainless steel from raw materials. Furthermore, other than welding or stamping we will not be able to modify the thickness of the steel available. The stainless steel will need to be cut into large sheets and then welded together. A suitable location would be selected, and the ground would be leveled and smoothed out with large rock's removed. The flat stainless steel would be placed on the ground as a large flat plate, perhaps 5km in diameter. Another plate would be placed on top of this one. Around the perimeter there would be scaffolding that would permit a radius of curvature to bend the two ends of the plates to be welded together. Thin metal sheets can have a relatively tight curve and remain elastic.

Underneath the top sheet would be a voids in the center with equipment. A small low-pressure atmosphere of perhaps 100mbar would be added which would gradually lift the top plate up. On top of the plate, in a controlled fashion, regolith would be added as the pressure below is gradually increased. The Dome would be allowed to raise up slowly, keeping it in tension but not allowing stresses to tear the corners where the top and bottom plates were welded together. In Chapter 3 we looked at how large of a curvature would be required for 4mm stainless steel and determined that a curvature of 2.35 meters was sufficient to make sure the material remained plastic. Adding some safety margin I would keep a minimum radius of curvature of 4m so that the structure can be fully inflated and assume a relaxed profile.

Finally, even though the structure might appear to be massive, it is very thin. Our 4mm thick shell would have about 3m of Martian regolith on top (about 6m for the moon) to offset 700mbar of the 800mbar internal pressure.

Whether the structure was placed on the moon or Mars, the low gravities, combined with the large internal pressure would tend to inflate the structure close to a sphere. If we load up the top with regolith so that the pressure difference between the outside and inside were reduced to 100mbar, the spherical "colony" would relax into a somewhat flattened sphere, the key parameter is to keep the smallest radius at 4m.

The construction techniques for large cities on the Mars and Moon can also be extended to truly massive size as we shall see when discussing lunar or Mars terraforming.

Underground- Craters, Caves and Underground Cities

While building a spherical city in a crater and covering it with regolith is one solution to the first large cities, there are other options. Considerable thought has been directed at building small and medium sized cities on the moon by using lunar caves to place habitation structures. This would eliminate the need for covering the city with Regolith, but the need for pressurizing remain so some sort of spherical structure built inside the cave will still need to be built. Furthermore, because the regolith is not on top of the structure, our structure will again be small. It is likely that lunar caves will be primarily of use by the initial small colonies for radiation protection, but that larger, permanent colonies will be covered in regolith.

To date, over two hundred possible lunar caves have been identified. Many of these caves are associated with lava tubes. In the distant past when lava drained out they left extensive caves behind.

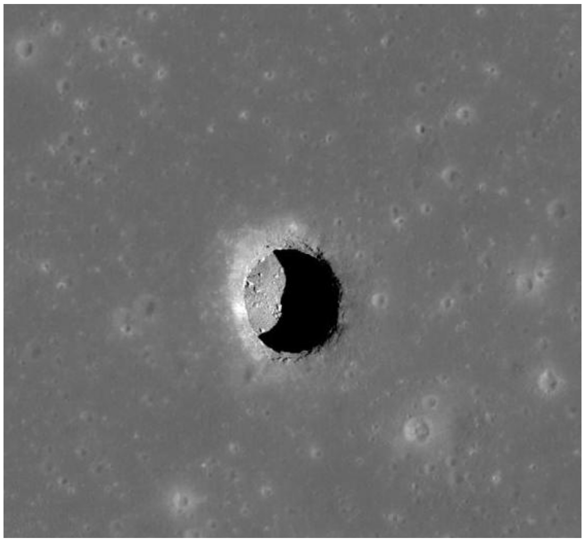


Figure 10-1 Skylight Pit in Marius Hills Taken by the Lunar Reconnaissance Orbiter (NASA/Goddard Space Flight Center)

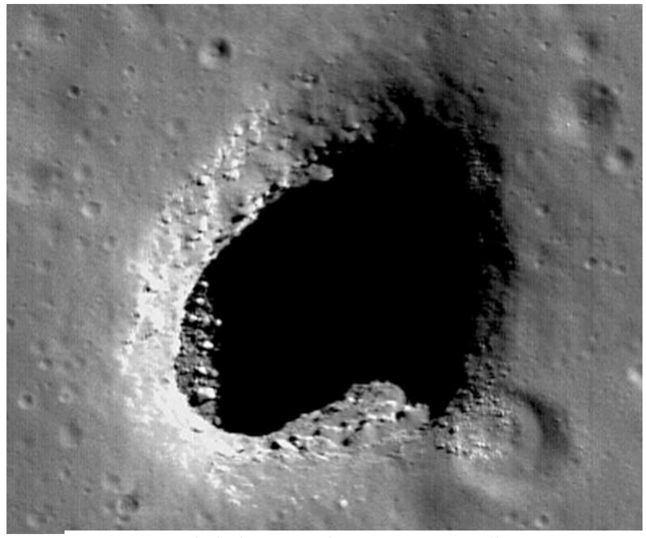


Figure 10-2 Skylight pit in the Mare Tranquillitatis (Courtesy NASA/Godard Space Flight Center)

At some point part of the lava tube roof collapsed, exposing the tube to the surface.

These pits are frequently very substantial in size. The pit in Figure 0-1 is some 400m wide. The pit in Figure 0-2 is approximately 65mx90m wide and 34m deep.

Living on Asteroids

Asteroids can serve as both a source of material as well as large colonies. However their low gravitational fields mean that you will either:

- Hollow the asteroid out and build a Bernal Sphere inside
- Build a Torus either rotating with the Asteroid and anchored to it with cables
- Build a Space Elevator that rotates with the Asteroid

Building a rotating Bernal Sphere inside a hollowed-out asteroid has tremendous potential. One reality of gravitational force is that when you dig beneath the surface, gravity is only the mass of the sphere below where you dig. In other words imagine a spherical planetoid 100km in diameter that is made 50 nested shells (like layers of an onion) each one kilometer thick. From the surface, all fifty shells are pulling down on you. But if you dig down one kilometer, only the remaining 49 kilometers is adding to your gravity, the entire top one kilometer shell around the planet is not adding any force. This means that when you dig down fifty kilometers your gravity would be zero.

If we took a modest asteroid about 21.4 km in diameter with a Specific Gravity of about 2.5, we would experience about 1bar of pressure at the center. This Asteroid would mass about 1.39x1016 kg.

If we hollowed this asteroid out and moved this material to the surface, we would build a rotating Bernal Sphere in the center of the asteroid. In theory we could pressurize this center to 1 atmosphere and then build a rotating Bernal Sphere where the inside and outside pressure would be the same-allowing for extremely large spheres since our normal equation for calculating stress is primarily driven by the difference between the internal and external atmospheric pressure. Our hollow core and the rotating sphere would have the same pressure allowing for a very large Bernal sphere.

Suppose we built a hollow core and a nested Bernal Sphere 15km in diameter and moved the core material to the surface. Our Asteroid would now be about 24km in diameter but have an internal void to place our 15km diameter Bernal Sphere inside.

An issue with this is that if the Bernal Sphere is nested within a 1 bar atmosphere and spun to give .9g at the equator, it will spin at about .33rpm and the equator will be moving at about 257mps- or Mach .75. This is very fast, will likely be very loud (even if care was made to make the sphere smooth) and will cause a lot of drag which will both slow the sphere down but also cause the air to start spinning in the interstitial which will tend to start the asteroid spinning (a constant motor will need to apply a restoring torque to keep the Bernal Sphere from slowing down and will also simultaneously offset the Asteroids spin up). This may be too large of a drag.

To get around this we will have to mitigate and compromise. The very act of transferring the core material to the surface will make the asteroid diameter and surface area larger, so that even though we made a hollow core 15km in diameter, our asteroids diameter only increased to about 24.2 km, so our top cover over the core will only be about 4.5km. We can therefore reduce our internal pressure. The equation to calculate this is:

$$P(r) = \frac{2\pi}{3} G\rho^2 (R^2 - r^2)$$

With:

$$R = 12100m$$

$$r = 7500m$$

$$\rho = 2500kg/m^3$$

$$G = gravitational\ constant = 6.674x10^{-11} m^3/(kg * s^2)$$

Solving we have only $7.9x10^4$Pa (.79bar) of lithostatic pressure. If we reinforce the inner cavity and lower the internal pressure to only .25 bar, our drag would only be about ¼ of the original value. Combined with a .8bar internal pressure of the sphere we will have a pressure component of only .55bar, better than a 1 bar or .8 bar limit. However, as we saw with our section on Bernal Spheres, we may want to reduce our structure a bit in size to maintain our margins. A Bernal Sphere 14km in diameter rotating within an asteroid about 24km in diameter is structurally feasible and would eliminate all concerns about cosmic radiation or meteoroid impact.

Asteroid Ring Worlds

For asteroids that rotate quickly, on the order of every two to three hours, it may be practical to build ring worlds. The primary challenge would be the requirement for high tensile strength materials like those for space elevators.

Let us assume a target gravity of 6.4 mps (65% earth). If an asteroid rotated at a rate of once every 2.2 hours, then you would need an anchored station about 10,170km above its surface to experience this gravity.

Resources

Power is in many ways the most important resource as without it you can't do anything else. However other resources are also critical including volatiles and metals. As we saw in Chapter 2, the raw materials that are contained in the Solar System are vast. Even the Asteroids have considerable mineral wealth and volatiles like water and Nitrogen.

Since the energy required to send kg of payload from the Earth to space is so high, most resources for our colonies will come from space itself. A very elaborate transportation and logistics infrastructure will need to be built.

Summary and Conclusions

Large Space Stations will be built to last centuries. The requirements for radiation protection and gravity, and to a lesser extent, meteoroid protection requires their mass to be very large meaning that they will require tremendous material resources. Space station living conditions will be close to earth but vary somewhat depending on their mission- for instance Mars Cyclers may be smaller and have a .65g.

In Table 10-1 we showed some typical design parameters. To this we can also add:

Volume of living space

- Permanent large colonies will be $500m^3$ per person
- Large cyclers and vessels occupied for up to 1-2 years $100m^3$
- Interplanetary Spaceships to be occupied for up to 2 weeks $10m^3$

Radiation protection for the smaller colonies will consist of 7 mt of regolith or water per m3 with no active cosmic ray protection. However, for many a supplemental active shield will be available that will reduce this, perhaps to as little as 3-4mt per m3. Spacecraft are likely to have no passive shielding, but radiation will be minimized due to short transit times, a small shield storm cellar if needed, and active shielding to reduce radiation by 25-50%. Very large colonies will need even less, due to the large mass of the stations, the thickness of the ground below and atmosphere above. Combined with active shielding perhaps only 2mt per m3 will be sufficient.

Mission	Type	Population	Gravity	Atmospheric Pressure	Power requirements / person	Comments
Geosynchronous Orbit	Stanford Torus	1000-250,000	.9g	800mbar	10 kW	Likely to support Space based solar power and tourism
Large L4, L5 Colony	Stanford Torus	100,000-250,000	.9g	800mbar	10 kW	Earth/Moon Lagrangian points
Large L4, L5 Colony	Bernal Sphere/O'Neal Cylinder	100,000-5,000,000	.9g	800	10 kW	Earth/Moon Lagrangian points

Lunar Elevator Anchor	Stanford Torus	1000-10,000	.65g	800	2 kW	Support tourism, embarkation for deep space missions
Mars Cyclers	Stanford Torus	1000-10,000	.65g	600	2 kW	
Mercury/Venus Cyclers	Stanford Torus	1000	.65g	600	2 kW	
Crewed Space Craft Transporters	Cylinder	10-1000	0G	600-800	2 kW	Depending on Mission; occupied for up to 2 weeks

Table 10-1

Chapter 11 -Logistics- Transportation and Mining

Cargo can frequently take longer to arrive at the destination, and is usually able to tolerate more challenging conditions (zero gravity, High and Low Temperature, High Radiation). As such, much of the cargo infrastructure will be separate from that used to move people.

Standardized Containers

One of the revolutionary concepts in shipping of cargo over the last 100 years was the development of standardized containers. These containers are steel boxes that can be stacked on ships or on land and lifted by specially designed forklifts or cranes. A TEU (Twenty Foot Equivalent) is a standardized cubic dimension of 20ftx8ftx8ft. Most containers are 2 TEU or 40' long.

Figure 11-1 2TEU container

For the large-scale shipment of cargo and mined materials in space, I believe an equivalent standardization of size and mass would be required. Our transportation infrastructure will be designed to handle a standardized container. For space the containers would be metric and would define both mass and volume. I will call these units SMTC (Space Metric Ton Container) and see there being three categories of ascending size:

1x1: 1SMTC- I cubic meter of up to NTE 1mt

10x10: 10SMTC- 10 cubic meter with NTE 10mt

100x100: 100SMTC- 100 Cubic meter with NTE of 100mt

These standardized containers could be either carried on spaceships as cargo, attached to a solar sail, or launched via a Mass Transfer Device or Mass Driver where they could be launched individually. In general, the 10SMTC would probably be the most common size.

A 10SMTC would contain up to 10mt of cargo, but the overall mass of a fully loaded container would mass about 11mt as they will consist of the container, as well as the cargo. I foresee this type being launched by a MT launcher, or mass driver but they can also be loaded on cargo ships or attached to a Solar Sail if this technology ever evolves enough to be useful. Some versions would be passive but most versions launched by an MT launcher or mass driver will be active and powered with some maneuverability and electronics. A powered SMTC (called PSMTC) of about 11mt would have:

- Totally loaded mass of 11mt
- Container will be designed to handle 10g acceleration
- 2kW of solar panels (about 6 m2), on opposite sides of the container for redundancy and flexibility
- Electric thrusters that provide 2000 Isp. Fuel will be Argon (or possibly Xenon) at 50% (η=.5) efficiency

- dV capability will be 450mps
- Argon Supply will be 250kg
- Transponder so device can be tracked
- Limited two-way communication ability; will be used to determine required trajectory modifications
- 2kwh battery
- Electronics
- Required target arrival accuracy of 1 meter
- Capture cable or hook

Calculating for Thrust at 50% efficiency:

$$T = \frac{2\eta P}{v_e} = \frac{2(.5)1000}{19613} = .051N$$

Calculating for Mass Flow:

$$\dot{m} = \frac{T}{v_e} = \frac{.0408}{19613} = 2.6x10^{-6}mg/s$$

Calculating for time of burn:

$$t = \frac{m_p}{\dot{m}} = \frac{250}{2.6x10^{-6}} = 9.62x10^{7}sec = 3.05\ years$$

This would maximize our dV but not be representative of a typical cargo trajectory. The dv capabilities are primarily to keep the container on a precise track for capture, so ideally only a small fraction of this quantity would be used, and depending on the delivery geometry, most of this Argon would be retained for future missions- replenishment would only be as needed.

The transponder would both transmit an identification signal for both a solar system wide tracking system (see Chapter 21), as well as for the target so that capture methods can be prepared. The Transponder would send out a signal once every 6 hours. The accuracy of this tracking system would be measured within about a 1 meter. This may not be feasible immediately after SMTC launch, but after several days of travel and repeated signals extremely accurate velocity and location information can be derived.

Approximate mass of equipment for a 10SMTC:

Item	Mass (kg)	Comments
Container Structure	550	Includes Capture device
Argon	250	
Argon container	10	Pressurized aluminum container about .7m in diameter; 2mm thick steel
Refrigeration/chilling equipment	25	
Battery 2kwh	15	
Solar Panels	60	2kw total, but positioned on opposite sides so only one will be exposed to sunlight at a time

Argon thrusters	45	Multiple small attitude thruster
Miscellaneous	45	Transponder, Electronics
Total	**1000**	**Empty container mass**

Table 11-1

Depending on the mode of transportation, shipping off large quantities of raw materials across the universe can be extremely low cost. Mass drivers or MT devices, once built, can operate at basically the cost of electricity. Installing large active containers will expand their useability and make space transportation colonization extremely practical. Besides transferring large quantities of supplies to colonies and Space Stations, using MT Drivers or Mass Drivers will enable spaceships to pick up resupplies deep in space.

If the container was designed for specialized service (perhaps to be able to provide a larger dv) the extra mass would come at the expense of payload. The mass of these containers would have a Not to Exceed (NTE)number associated with their size- on the order of 10% greater than the cargo mass. A container may mass less, we probably would need to add a nomenclature to identify the actual transported mass- something along the lines of 10SMTC5- which would be a 10 cubic meter container with a mass of only 5mt. The launch equipment, along with the receiving equipment will drive the size of the containers that can be handled.

These reusable containers would be manufactured in the tens of thousands or even millions and transported throughout the Solar System via a variety of means- to include Rockets of various types (chemical and nuclear), Solar Sails, Momentum Transfer (MT) Devices, and Mass Drivers (MDs).

Finally we need to consider the practicality and scale of shipping across the solar system. Lets assume that we have an operation that can dispatch 10 ten-ton cargo pallets an hour. Assuming our total container mass is 11000 mt, we would need 27.2 MWh per launch. In one hour we would need a 272MWh power plant. This would ship 100,000mt or $1x10^8 kg\ per\ hour$.

Summary and Conclusions

There are many technologies that will need to be developed and used. The successful conquest of space will require these improvements in technology:

- Lightweight fission reactors, of at least 20w/kg of energy production.
- Large fission reactors of MWe and GWe generation
- Materials development of extremely strong and lightweight materials for solar sail development and space elevators as well as for Mass Transfer spin arms

The development of lightweight and powerful fission reactors are feasible, with no major technological issues, but severe manufacturing issues… no large reactors have ever been built for space.

Extremely strong and lightweight materials development is more speculative. While materials development will continue to improve, whether they can achieve the orders of magnitude improvements required is more questionable. In reality, solar sail materials need to be at least ten times lighter for the equivalent strength of current materials, and space elevators will need materials at least ten times stronger than steel to make elevators possible on Mars, let alone Earth which would be vastly more difficult.

Solar Sails have tremendous potential for both large and small spacecraft but await the development of extremely strong but lightweight materials.

Chapter 12 - Terraforming the Earth

Terraforming

Terraforming is the process of modifying a planet or moon to make it more conducive to life, in particular, humans. Ideally the goal is to bring a planet or moon environmental condition to a level like that which we experience on earth, permitting humans to exist on the surface with little or no protection from the environment.

In theory a completely terraformed planet would closely mimic the earth and address the following:

Characteristic	Earth Surface Standard	Comments	Acceptable Range (target)
Gravity similar to Earth	1g (9.81mps)	Not achievable unless planet built from scratch	.15g?-1.1g (.8g)
Solar thermal radiation similar to Earth	1400 watts m^2 (100,000 lux)	Would require Solar Occulus or Solar Mirrors	20%-100% Earth (30% Earth)
Length of Day similar to Earth	24hrs	Solar Occulus and Mirrors	12hrs?-48 hrs?
Atmospheric Pressure Similar to Earth	1000mbar	Release of volatiles from planet/moon surface; importation of volatiles	350mbar-2000mbar (800mbar)
Atmospheric makeup similar to Earth	80% Nitrogen; 20% Oxygen	For atmospheric pressure below 800mbar increase oxygen ratio	Oxygen 20%-60% (depending on pressure)
Surface make up similar to Earth	To include water	Large scale earthworks; release or importation of water	
Radiation Similar to Earth		Imported atmosphere	0-200% Earth Levels (<100%)

Table 12-1

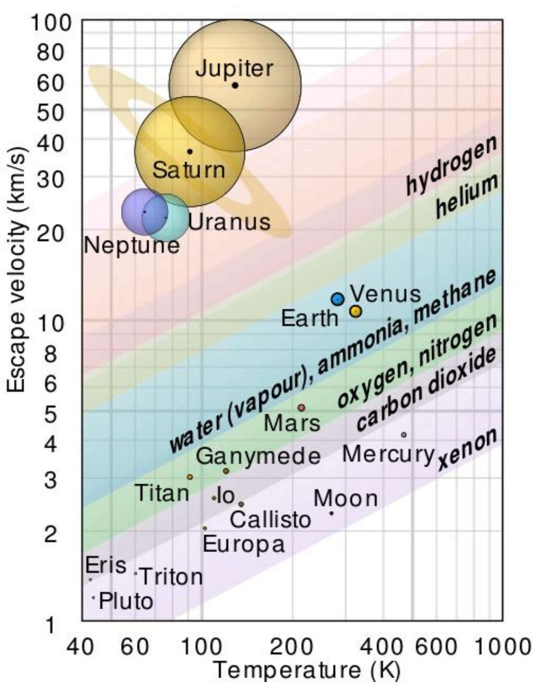


Figure 12-1

In all cases, modifying a planets/moons surface condition is not permanent- and will require constant human technological intervention to remain within the target range. Since all planets or moons that are prime candidates for terraforming are smaller than the earth, gravity is less (and frequently much less) than the earth. In many of these cases, any imported atmosphere will, over the course of thousands of years, bleed out. Table x-2 shows us that most planets/moons cannot keep an Oxygen or Nitrogen atmosphere unless they are kept very cold. The very process of warming a body will cause the atmosphere to be lost faster. Furthermore, most planets/moons that we would like to terraform lack a magnetic field. The Earths magnetic field helps to reduce the atmospheric loss over time. In Chapters 13, 14 and 15 we will look at the challenges and limitations of terraforming various bodies in the solar system.

Terraforming the Earth

When we speak of terraforming we usually are talking about planets and moons other than the Earth. However, the Earth is the one planet that we are actively terraforming-albeit inadvertently, with CO2 emissions. The earths' atmospheric CO2 levels have increased substantially over the last two hundred years- about doubling since the mid-1800's. This has led to an inadvertent rise in global temperatures due to the fact that CO2 is a greenhouse gas and helps the earth maintain its relatively balmy 15C average temperature. Using the Stefan-Boltzmann calculation from Formula 12-1 and assuming no atmosphere we can see that the average temperature of the earth would be about 255k or -18C assuming an albedo of about .3. Note that what we saw in Figure 2-6 was that without greenhouse gases the Earth would average about 279k- this discrepancy is probably accounted for by a differently assumed albedo of .25 instead of .3. On balance, global warming has helped the planet by lengthening the growing season, increasing the CO2 levels which plants need to grow, and reduced the amounts of deaths due to cold. With that being said, it is also causing still undetermined and potentially negative consequences with increasing temperatures leading to substantial glacial melting and the possibility of oceans rising.

EARTH			Comments
Diameter			
Mass			
Surface Gravity			
Escape Velocity			
Density			
Atmospheric Pressure			
Atmospheric Composition			
Length of Year			
Length of Day (Solar)			
Orbital Velocity (around Primary)			

Table 12-2 Selected Specifications of Earth

Most of the most environmentally and economically optimum solutions to lower greenhouse gases conclude that Nuclear Power is the best solution. However, for a variety of reasons, political and educational, Nuclear Power has not been pursued aggressively over the last thirty years. During the 1970's up to forty nuclear power plants constructions were being started per year. The pace plunged so that by the early 90's only 2-3 were being started per year (International Atomic Energy Agency, 2024, p. 88). In the early 21st century this pace has bounced around from 3-10 per year. If the pace of the early 1970's had been maintained, most if not all coal plants in the world (and all those in the US) would have been phased out by early in the 21st century.

In this Chapter we will look at several intentional Earth Terraforming scenarios, the design of which is to either eliminate or minimize the unintended global warming, or to directly reduce the temperature of the earth. There are four basic approaches to reducing global temperatures- three of they would be considered terraforming. The four scenarios are:

- Conversion to earth based Nuclear and Solar to reduce the amount of fossil fuel emissions
- Increase of the Earth Albedo to increase reflectivity and lower temperature
- Building large Space Based Solar Power to beam energy down to earth and eliminate the need for fossil fuel power plants
- A Solar Occulus to reduce radiation falling on the earth.

The first item is strictly a continuation of what we have now- the next three are covered in the rest of this chapter.

Explanation of Global Warming- Heat Balances

Effectively all energy that warms the earth comes from the fusion fire of the sun. It is true that very small amounts of heat come from within the earth, the residual heat of its formation as well as the radioactive decay within the planet, but these quantities are relatively insignificant.

The earth's surface temperature is kept in balance because the heat it receives via the sun is exactly balanced by the heat emitted from the atmosphere and ground. During the day enormous quantities of solar radiation add heat to the atmosphere and ground. Some of this is reflected back into space immediately, but some of this heat is retained for a while until discharged. At night, the earth continues to radiate the heat accumulated during the day, bringing the atmospheric and surface temperatures down.

At the distance of the earth from the sun, the average amount of energy received is 1360w/m2 for a flat plate directly perpendicular to the sun's rays. Because the earth is curved, and half the earth is dark at any one time, the actual average energy received over the earth's surface is about 340w/m2 (Lindsey, 2009).

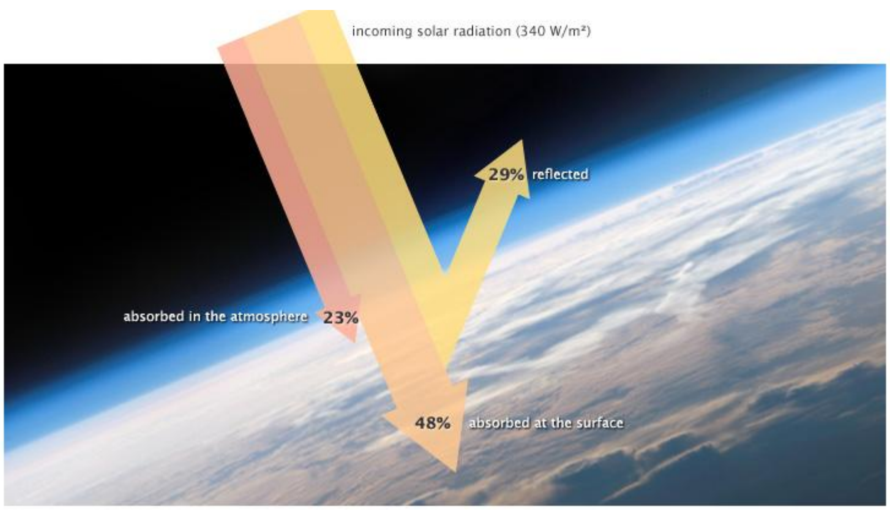


Figure 12-2 (Lindsey, 2009)

Of this quantity, about 29% is directly reflected back into space, either from the atmosphere or from the ground, and plays no role in heating the planet. The rest is retained by the atmosphere or the surface where it warms the planet up. As the atmosphere and ground heat up, they emit more infrared radiation until the emitted radiation is sufficient and equivalent to the amount of heat arriving and the earth has reached equilibrium.

Anthropomorphic Climate Change

Almost by definition, the climate changes and always will. Putting aside the question of whether human caused climate change is fundamentally worse than natural climate change, there is widespread agreement that humans are changing the climate- primarily through the tremendous increase in CO2 levels in the atmosphere released through the burning of fossil fuels. Over the history of the earth, CO2 has been scrubbed from the atmosphere through various means so that the CO2 levels have decreased substantially over the eons. Until humans, the primary means for replenishing this lost CO2 was volcanic activity. Over the age of the earth, large quantities of CO2 have been sequestered by living organisms that, when they died, were covered either by the next generations of dead organisms or dirt, silt or volcanic ash, thereby removing the CO2 from the atmosphere. Over millions of years this carbon was driven deeper and deeper into the depths of the earth where they were subject to high temperatures and pressures which converted into items like coal and gas. The drilling for oil and gas or the extraction of coal brings this material back to the surface where, when burned, release this stored CO2 back into the atmosphere.

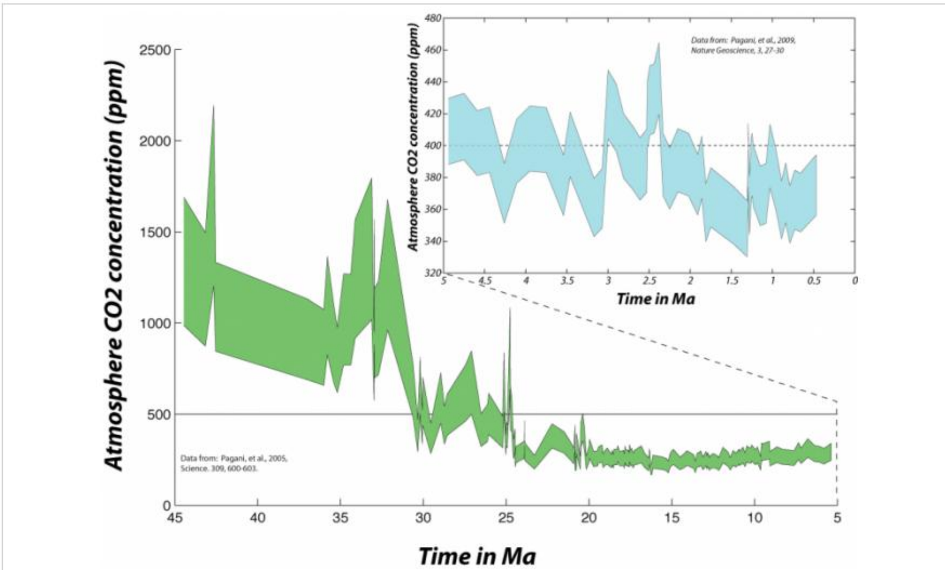


Table 12-3 (Pagini)

CO2 (or specifically Carbon) in the atmosphere is the primary structural material for plants and trees. As the earth gets older and CO2 gets removed from the atmosphere and buried, the CO2 levels will gradually drop, eventually so low that plants can no longer survive, and all plant life (and all those animals that live off the plants) will die. It is estimated that this will occur within anywhere from a few million to one billion years. The burning of fossil fuels temporarily counteracts the long-term tendency towards reduced CO2 levels.

On the earth, some of the sun's incoming radiation is immediately reflected back into space, and some gets absorbed into the ground and atmosphere. The ground reradiates its heat either directly into space or into the atmosphere where it is re-absorbed. This absorbing layer will emit 50% of this radiation back up into space and 50% back down to the ground. If the make-up of the atmosphere changes through changes in CO2, water vapor, etc., the atmosphere can trap more heat, preventing the ground and lower atmosphere from cooling. The surface warms up, and eventually this increase in temperature will cause the atmosphere to warm up, increasing the heat emitted at the top of the absorbing layer (remember 50% of the heat is sent up). Venus emits exactly as much heat as it receives and maintains its blistering heat because it has to. When Venus originally heated up it was because the greenhouse gases prevented efficient radiation of the surface heat back into space, eventually increasing the temperature of the re-radiating atmosphere. All planets must reach equilibrium temperature with the heat received, but the equilibrium can vary with surface and atmospheric reflection, and ground and atmosphere radiation.

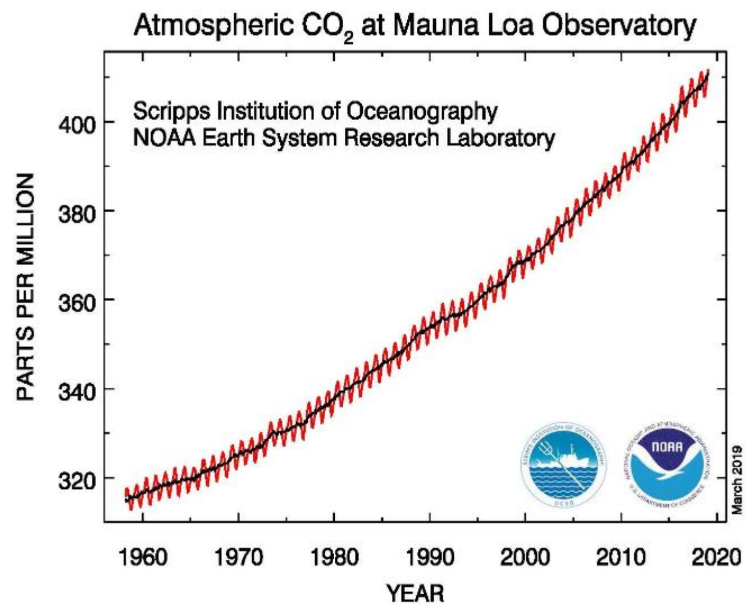


Figure 12-3 Atmospheric CO2 Levels (Courtesy NOAA)

The CO2 levels currently being experienced are the highest in the last twenty-five million years (figure 0-2 and 0-3). Historically the earth has had periods where CO2 levels have been much higher than current levels- so high that during certain periods the earth had no major ice sheets. Over the last forty-five million years there have been spikes of over 1500ppm. Over the last six hundred million years CO2 levels have been even higher- occasionally over 5000ppm (Figure 0-5). Nevertheless, the increase over the last century has been impressive (Figure 0-3). Technically the climatic situation over the last few million years has been defined as an ice age as large ice sheets have covered parts of the globe- primarily Antarctica and Greenland. During periods of higher CO2 levels- say about 30million years ago, there were no large ice masses and sea levels were 100m higher. (Bice, n.d.)

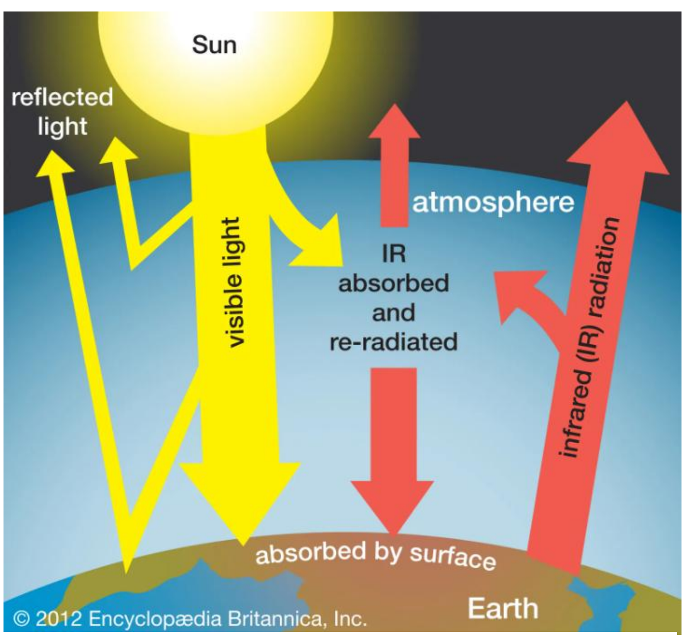


Figure 12-4 Greenhouse Effect (Courtesy Encyclopedia Brittanica)

The question for us is if the disadvantages of human caused warming are worse than the natural climate change. In general, the idea that the increase in atmospheric CO2 as well as the impact this has on the climate (warming) is uncontroversial. More controversial are the conclusions- that the disadvantages of human induced climate change are worse than climate changes that would be occurring naturally. If it were not for the current increase in CO2, the world would be colder and less habitable. Offsetting this, a cooling planet would not have rising sea levels as a threat. Furthermore, the rate of increase in CO2 levels is extremely rapid and unprecedented over the last twenty million years or so. Historically the few exceptions to this statement were when major volcanic eruptions injected massive quantities of CO2 into the atmosphere.

The increase in CO2 levels brings with it the risk of global warming which can be disruptive to human civilization as well as putting stress on natural ecosystems. However, there are two related issues that have two different solutions- is the concern with global warming or more with the concern about raising CO2 levels? If CO2 levels were not causing an increase in temperature, some would argue for the reduction of CO2 levels anyway. However, the public as well as politicians use the specific issue of global warming as the priority and not the increase in CO2. Each of the two space-based solutions in this article address a different aspect of human induced climate change. If global warming is a concern, then a Solar Occulus or SBSP can help- indeed it could likely prevent global warming for centuries. If, however, the concern is increased CO2 then only the SBSP will be an effective solution.

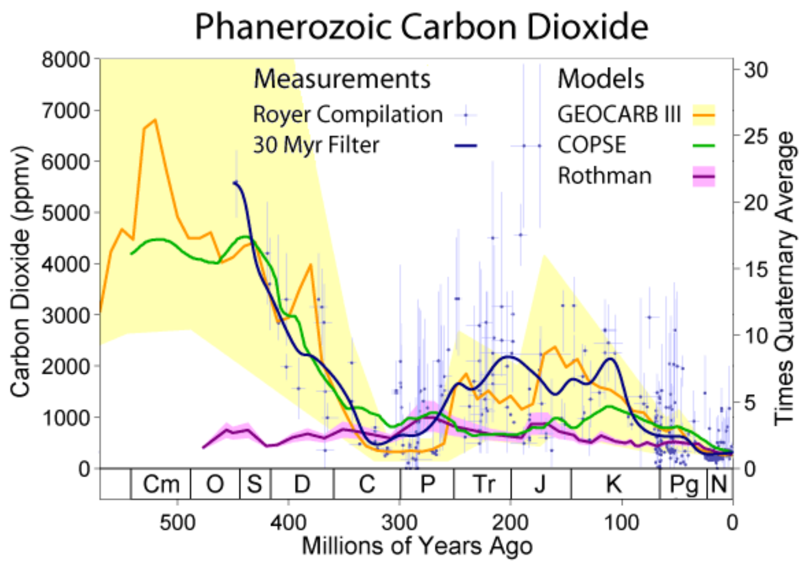


Figure 12-5 (Rohde, Robert A)

Albedo changes

One possible relatively inexpensive solution that has not been pursued except in small scale experiments is changing the earths' albedo. This would be accomplished by making the earth's surface or atmosphere more reflective. For instance, farm land is more reflective than forests so it may make sense to cut down forests and replace them with grass. Alternatively, there are means of increasing cloud cover or the reflectivity of the atmosphere through high altitude aerosols. This is an area that requires further research and experimentation before it can be decided on the feasibility and desirability of the diverse options. An albedo change would primarily address the issue of global warming and would not be of any help in reducing CO2 emissions. Note that by only a slight modification of the earths albedo, we can either raise or lower our temperature. Indeed, increased forestation can lower albedo, and further compound the greenhouse effects by lowering the grounds reflectivity. However, in general, eliminating the forests would make the situation worse as any increase in reflectivity would be more than offset by increased CO2 as trees sequester a lot of carbon dioxide and would have to be burned or somehow used in order to get rid of them.

Space Based Solutions- Space Base Solar Power (SBSP)

There are two space-based solutions that can make a meaningful impact to global warming- building large Space Based Solar Power Systems (SBSPs) which would provide greenhouse gas emission free energy, and a Solar Occulus which will serve as a shield to reduce solar radiation and permit a cooler planet. Both, but especially the Solar Occulus can be considered a small-scale terraforming- far smaller in scope and cost than Terraforming Mars or the Moon, but very substantial, nonetheless.

Space Based Solutions- Space Base Solar Power (SBSP)

Beamed Solar, or SBSP, has been widely recognized since the 1970's as an extremely promising real-world application for the space industry. Its advantages over earth based solar power are substantial and include:

- The Sun's solar radiation is much stronger in space than on the surface of the earth.
- Depending on the placement of the SBSP, solar radiation may be uninterrupted eliminating the need for power storage devices like batteries or storage reservoirs.
- It moves large infrastructure off earth thereby saving land. (Note the SPSP receiving stations will be quite large but can be placed in remote areas, and like wind turbines, the land beneath the receiving rectennas can be used for limited purposes)

The issue with beamed solar is that to provide meaningful power the power station needs to be extremely large and typically requires all the materials to be launched from Earth. In order to minimize power interruption, they are conceived to be placed in geosynchronous orbit where they would be blocked by the earths shadow only a few times per year. The electricity generated by the solar panels would be converted to microwaves and beamed down to a receiving rectenna station on earth.

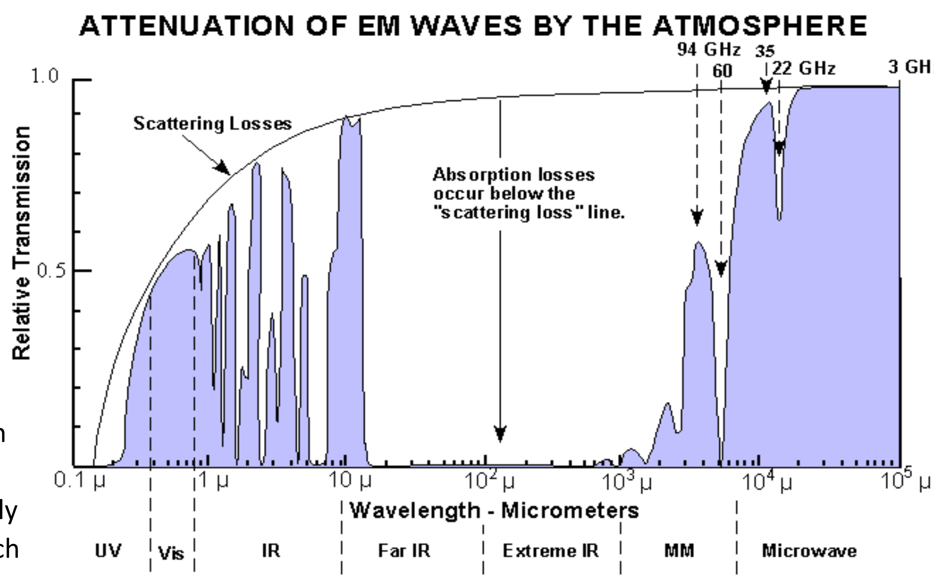


Figure 12-6 Attenuation and Absorption of EM Waves (Courtesy of US Navy via Wikipedia)

For planning purposes, let us assume we would like a baseline 10GW power station- equal to that of ten large earth based nuclear reactors. If we assume a solar panel efficiency of about 24% (the efficiency of current solar cells for spacecraft) and a power transmission efficiency of 85% we will need to have an extremely large SBSP mass (but much smaller than an equivalent earth-based plant). To get 10GW of useable power we would need a power plant able to collect the equivalent of nearly 50GW of energy.

Let us assume we receive 1400W/m^2 in our orbit. With 24% solar cell efficiency we will be able to create about 336W$_e$/m2. With 85% beam efficiency we are down to 286W$_e$/m^2. This power would be beamed down to the earth via microwaves. For 10GW we will need 3.4965x10^7 m^2- or a square solar panel 5,913m^2- 5.9km on a side.

The solar arrays on the international Space Station mass around 2400 lbs. (1087kg) and each generate about 31,000 Watts, or 28.5 W/kg (NASA Shuttle Press Kit, 2001). The very efficient Juno Spacecraft generated about 35W/kg for its solar panel. Using this more efficient number we can calculate that our mass will be 2.857×10^8kg or 285,714 mt. This would work out to about 8 kg/m^2 for the solar panels.

To launch this from earth would be extremely expensive. Currently the published launch costs for a Falcon 9 are about $67million for up to 22,000kg to orbit- this works out to $3050kg. This number is far too expensive to justify constructing an SBSP station. However, Elon Musk has stated that the new fully reusable SpaceX Starship costs will be much lower- target payload in the range of 150mt to orbit for $15million which would only be $100kg. At the ambitious cost of $100per kg our launch costs would be $28.6 billion- large but not unreasonable. Note that Elon Musk has stated that to build the colony on Mars he believes a minimum of a million tons will be required to be launched to orbit so the number of launches for a SBSP station is large but less than that being considered for a Mars colony.

In order to get the all-in costs, we need to add the development costs for the design of the solar power facility as well as the earth receiving station. The receiving station would need to be large as OSHA regulations limit the amount of microwave exposure for humans to 250w/m^2. The earth's atmosphere is transparent to microwave- per Figure 0-12 it can be seen that at about 30mm (10 GHz) and longer- in what is the microwave range- the atmosphere is transparent and beaming down energy via microwaves with low losses are feasible. A 10GWe ground receiver will require 40 million m^2 (40km^2) or a square receiver 6.3km on a side. The receivers can be built in the desert or may even be able to be built on farm land as with wind turbines, the land below and around the receiving rectennas can still be used.

The development cost burden for this would primarily be absorbed by the design of the first power plant. Let us assume about $20 billion in development costs are required.

SBSP Unit	**Launch Costs $B/mt**	**Developm ent Cost $B**	**Manufact uring Costs $B**	**Incremen tal Costs $B**
1	29	20	29	77
2	26	0	26	51
3	23	0	23	46
4	20	0	20	40
5	17	0	17	34
6	14	0	14	29

Table 12-4 SBSP costs sequential 10GW_e units; launch and manufacturing costs are assumed to be $100kg for first Power Station and decrease by $10kg for each subsequent launch until $50kg is hit.

To this we need to add the actual construction of the solar power plant, including the solar panels, structure, and microwave transmitters. According to Global Com (Global , n.d.)a weather satellite costs about $290million- or for a 3mt satellite almost $100,000/kg. Conversely, Musk has indicated that a Starlink satellite costs less than $250,000 each (Wang, 2019). The latest version of Starlink, V1.5 weighs 306kg which indicates a cost of $816/kg. Their Starlink system already has many thousands of satellites mass produced at relatively low prices.

Let us assume that for a large power plant we will have additional economies of scale and can get the cost down to $100kg. In this case our first 10GW$_e$ satellite manufacturing costs total would be about $77 billion.

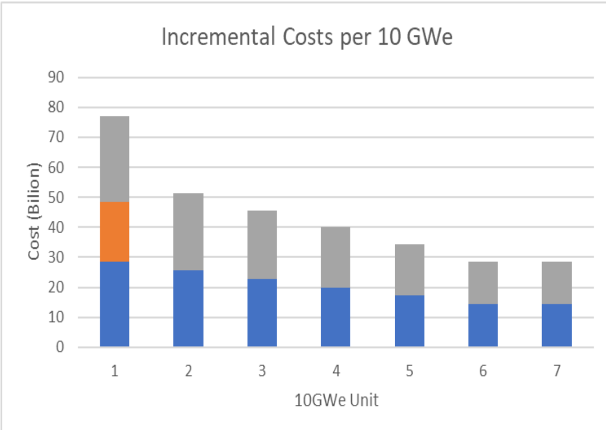


Figure 12-7 Graph of Incremental Costs

After this first unit is built, launch costs are assumed to drop by $10kg for each additional SBSP (or about every 1900 launches) until a final cost of $50kg is reached. For the commercial airline industry, costs vary wildly depending on distance and aircraft type, but a typical aircraft may fly a 100kg person for a $500 ticket which implies a cost of only $5 per kg. While this seems unrealistic for a rocket, I do believe that if we were launching thousands of ships per year, additional savings of on launch costs could be achieved. Elon Musk, in 2020, stated his goal would be to eventually launch a Starship for $1.5 million which equates to only $10kg. Table 0-1 lays out the unit price for the first 6 10GW$_e$ units. Note that this figure is optimistic, as it assumes that there is no cost to raise the Solar Power system to Geostationary orbit. In this estimate I elected to assume that the station is built in low earth orbit, around 500km. It will be raised by a large electric ion thrust engine at its construction conclusion, using power generated by the SPSP. This ion engine is many orders of magnitude larger than has ever been built but their should be no technological hurdles, but their will be some design and development costs which should be relatively small.

After the first article is built, development costs would go to near zero. Furthermore, I assume that the manufacturing costs will drop, as we get additional efficiencies with each additional power plant constructed by implementing lessons learned, economies of scale and manufacturing improvements. As with the launch costs, I show manufacturing costs drop linearly by $10 kg for each SBSP plant produced until a final cost of $50kg is reached by the sixth unit. A 50% reduction would be reasonable. The F-35 aircraft programs initial articles were reported to be in excess of $160million per aircraft in the initial lots but the latest contracts indicate a price of about $80 million (Harper, 2019) per aircraft.

This will drive the sixth and subsequent unit price down to about $29 billion a piece. After this, fixed costs, the launch fuel, normal maintenance costs and diminishing returns will level out the price reductions.

In 2024 the average cost of electricity in the US was 16.2 cents per kwh (US Energy Information Administration, 2023). Assuming a SBSP station generated an average of 10GW$_e$ (or 87.6 TWh annually), this equates to about $14.2 billion in revenue. The ground station is low tech and should be relatively inexpensive to operate and the SBSP platform, if designed for 30-year operation with minimal repair costs, will have moderate reoccurring operating costs- assumed for our purposes of only $2 billion per year. Further, let us assume that we incur additional planned maintenance expenses requiring launches to the SBSP station for programmed repairs every five years that cost an additional $3billion. Assuming a discount rate of 8% for a 30-year life and calculating NPV, IRR and Payback we come up with the following:

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cash Inflow		14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
Cash Outflow	-77.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0
Net Cashflow	-77.0	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2
Cumulative Cash Flow	-77.0	-64.8	-52.6	-40.4	-28.2	-19.0	-6.8	5.4	17.6	29.8	39.0	51.2	63.4	75.6	87.8	97.0

Year	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Inflow	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
Cash Outflow	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0	-2.0	-2.0	-2.0	-2.0	-5.0
Net Cashflow	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2	12.2	12.2	12.2	12.2	9.2
Cumulative Cash Flow	109.2	121.4	133.6	145.8	155.0	167.2	179.4	191.6	203.8	213.0	225.2	237.4	249.6	261.8	271.0

Discount Rate	8.00%
NPV	54.59
IRR	15.04%
Payback Period	6.6 years

Table 12-5 NPV, IRR Payback Period for 10GWe $77 billion first article

Follow up units will be cheaper and have payback periods even faster. Based on this rough analysis it would appear that large SBSP stations can be economically viable once launch costs and manufacturing costs come down to the range of $100kg.

Comparisons With Ground Based Solar

Installing a square meter of SBSP panel will be much more expensive than an equivalently sized ground-based panel. However, it is much more efficient and generates far more power per meter of panel. On average a SBSP station will receive about five times more power per square meter than a ground station (1366w/m^2 vs 250 w/m^2) when averaged over 24 hours. There will be some power transmission losses on SPSP so we can adjust down to about four times more power. Unfortunately, published reports on the costs of land based solar power do not list a constant baseload cost so as to compare it to other forms of power (SBSP, Nuclear, Gas, Oil and Coal). A large solar ground station will need to have substantial storage capacity to save a portion of its energy to provide power at night and on cloudy days- easily doubling the installed cost. Published reports indicate that installed solar roof panels generate power for $.07 kwh, or half the average price of electricity generated in the US. If this were true, all power would be generated by rooftop solar panels and subsidies would not be needed. However, the truth is that these prices do not include power storage but only the instantaneous peak power generated for the house consumption or is fed back into the grid. To compare Solar to other forms of power generation we would need to include power storage in our total costs, which will likely triple costs to about $.21 per kwh.

An SBSP does not need this storage capability- therefore to generate the same returns a space-based solution can be about twelve times more expensive to build than a ground solution for each square meter of generating power.

I also wanted to look at the energy required to launch the SBSP. If it takes more energy to launch the 286k mt into orbit than the energy produced over the lifespan, then it will not be advantageous to build an SBSP. Using the SpaceX Starship as a template, I assume that the v3 Starship will put about 150mt into orbit for each launch. To put this much into orbit requires about 5000mt of methane and oxidizer. Over 1900 launches, this equates to 9.5million mt of fuel and oxidizer. This assumes (overoptimistically) no additional fuel is required to transfer the SBSP from low earth orbit to geosynchronous orbit. The specific impulse of the methane fueled rockets are about 380seconds, so the exhaust velocity would be about 3800mps. Using our equation of Kinetic Energy,

$KE = \frac{1}{2} mv^2 = \frac{1}{2} (9.5x10^9)3800^2$

$KE = 6.859x10^{16}$Joules

This works out to 68.59 Petawatt sec or about 19TWh. Our 10GWe SBSP generates about 88TWh annually so within about 2.6months it would generate more power than is required for launch.

Space Based Solutions- Solar Flux Reduction-The Solar Occulus

The continued growth in energy usage in the third world combined with limitations of each of the "green" solutions discussed means it will likely be nearer to the end of the century before CO2 levels even out and start decreasing. It is likely that all of the options discussed will be part of the solution to meet the long-term goal of significantly reducing CO2 emissions.

For these reasons I wanted to look at the feasibility of a quick, lower-tech, shorter term fix. Like the proposal for increasing the earth's albedo, this fix would not address the increasing CO2 levels but would address the global warming issue and would be able to address it quickly- within the next twenty years. Instead of trying to create greener power or increase the earths' albedo we would instead reduce the solar flux impacting the earth in order to reduce the earth's temperature.

Suppose we blocked 2% of the sun's energy with a large solar shade (which I will refer to as an Occulus because it sounds better than a solar shade)- how would that effect our temperature? Using the Stefan Boltzmann equation, we can calculate the temperature change. The Equation for calculating temperature for a body at the earth's distance from the sun is:

Equation 12-1 $T_T = T_{\odot}\sqrt{(\frac{R_{\odot}}{2R_T})}$

σ is the Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^2K^4)

R_{Θ} is the radius of the sun in meters. This is 696×10^6 m

T_{Θ} is the temperature of the sun in Kelvin. The surface temperature of the sun at R_{Θ} is 5780K

R_T is the distance of the earth from the sun- or about 1.496×10^{11} m. CC

$$T_T = 5780\sqrt{(\frac{696x10^6}{2(1.496x10^{11})})}$$

Or a temperature of around 278.8K. This is called the effective temperature and assumes all energy hits the ground, that the earth is a perfect absorber, and there is no atmosphere. In reality the earth reflects about 30% of the energy and the actual temperature would be 255k.

For our calculation we can assume the effective temperature of a perfect absorber without atmosphere. For an Occulus that reduced the solar flux by 2% (the equivalent of increasing our planet's orbital distance by about 2% or 1.523×10^{11}km) our planet's temperature would be 276.3K or a decrease of 2.5C. This comfortably spans the projected temperature increase over the next century.

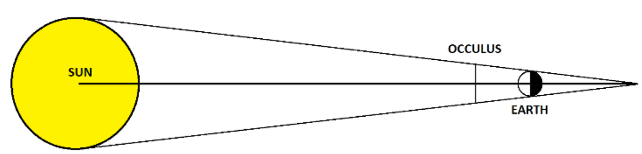


Figure 12-8 Sun Earth Occulus Geometry (Not to Scale) for a 100% occultation

Before we determine where to place the Occulus, we need to revisit the Lagrangian points first discussed in Chapter 3.

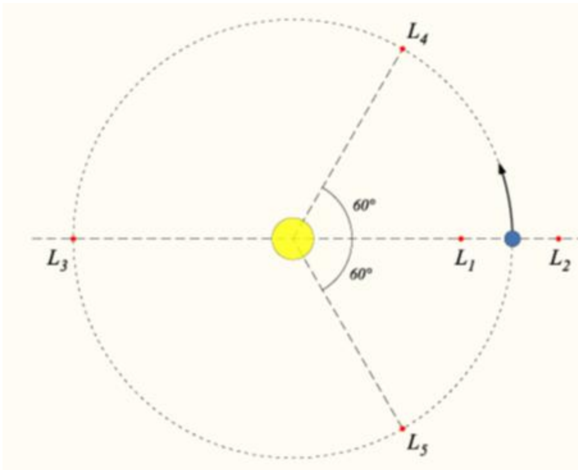


Figure 12-9 Occulus would be located just inside the L1 position

To accomplish this required reduction in radius, a large Occulus would be need to be placed just inside the L1 Lagrange point. Putting the Occulus inside the L1 point is required because the large surface area and relatively low mass of the structure means that it will experience some light pressure as with a Solar Sail. Using Formula 3-11 we can calculate this point being about 1.5million km inside the earth orbit, or about 1% of the distance between the earth and sun (Figure 0-15). We will need to add a small additional distance to counterbalance the solar pressure but this can not be calculated until a material is selected and we know its density and reflectivity.

At approximately 1.5million kilometers sunward from the Earth, to fully oculate the sun a shade would need to be considerably larger than the sun's diameter. A similar effect can be observed during a total solar eclipse… where those in the so-called umbra see a total eclipse but anyone outside in the penumbra see only a partial eclipse. This is because, even though the moon's apparent diameter is about the same as the sun it fully blocks the sun over only a very small part of the earth's surface along a narrow path of totality. The geometry of the Earth and L1 position mean that to fully block out the sun everywhere on earth the diameter of the Occulus would need to be much larger than the apparent diameter of the sun- or about 28,000km- appearing from Earth about twice the apparent diameter of the sun when positioned at L1. This would ensure a complete shadow of the earth even at the poles. The actual geometry for a fully eclipsing Occulus is shown in Figure 0-14 and would have an incredible area of 615,752,160 km^2 ($6.1575x10^8$ km)

Fortunately, we need only to block 2% of the sun's radiation and would require a more manageable but still huge area of $1.2315x10^7$ sq km. The diameter for such a device would be 3,960 km. At dawn such an Occulus would appear as a black chip off the sun's edge. As the day advanced the chip would gradually move across the sun's face, until it appeared as a large dark mote on the sun's face (see Fig 0-16). In the course of the day, it would continue to migrate across the sun until by dusk it would appear as a chip at the side opposite of the dawn position. From a place directly below the shadow of the Occulus the shadow would be quite large- however, as with the change in the time of day, depending on the latitude, the Occulus will appear either above or below the solar equator.

How massive would such a structure be? With high performance solar sails engineers are looking at materials that mass less than what the local solar gravity force is- about 1.53 g/m^2 (or $1.53x10^{-3}$ kg/m^2). This is also called sail loading. This ambitious requirement is one of the reasons solar sailing has not been seriously applied for space travel. Some of the best materials currently available and considered for solar sails mass about $7g/m^2$ (mylar). For our Occulus, we could assume an even less ambitious material that when combined with a rigid structure masses $10g/m^2$. For a 1km shade we would mass $10mt/km^2$. Using this our total Occulus would mass $12.315x10^8$ mt. However, the shear size of the Occulus means that many metric tones of material would be required and even a lightness number of 10g/m3 would require some sort of artificially manufactured material that will likely be made of carbon fiber. Furthermore, most instances where we would build such a large structure the intent would be for it to last for centuries. It may be more practical to use a more common material like aluminum, titanium or steel. These do not weather very quickly in space and therefore much more durable while also be much easier to make as the raw materials are abundant.

We must therefore use the thinnest material possible to minimize weight but have it thick enough to survive for centuries. This will also drive the need to maintain its shape primarily from centripetal forces-building a rigid structure with beams and trusses would add substantial mass. The issue is to rotate the Occulus slowly, allowing the centripetal force to keep the surface flat. This also means that the material used along with its radius will determine the rotation rate.

The aluminum on the Apollo Lunar Module crew compartment was .3mm thick. We may want to make the sheets somewhat thicker as we would like to see them last for centuries. Let us derive the Occulus Mass based on some possible materials.

Material	Density	Mass per square meter at .5mm	Mass (mt) per square kilometer	Total Mass based on $1.2315x10^7$ sq km	Comments
Light Sail Target		.00153	1.53	$1.8842x10^7$	
Artificial Fiber		.01	10.00	$1.2315x10^8$	
Aluminum	2700	1.35	1,350.00	$1.6625x10^{10}$	
Steel	7850	3.925	3,925.00	$4.8336x10^{10}$	
Titanium	4500	2.25	2,250.00	$2.7709x10^{10}$	

Table 12-6 Assuming a uniform Occulus material thickness of .5mm

The exact material used will depend on a detailed analysis of durability, cost of manufacture and the cost of transportation and assembly. If the sheets are created by refineries on the moon and launched via a spin launch system (see chapter 6) transportation costs could be very low and aluminum, steel or titanium would be all in the running. If the materials had to be launched from earth, we would probably go to the artificial composite materials mentioned above.

How would such a structure be constructed and what would be its stress? Since the structure is quite thin to keep mass reasonable but will need to stretch for thousands of kilometers the structure would probably rotate slowly with centripetal force keeping it flat.

$$\sigma_{\theta} = \frac{3+\nu}{3}\rho\omega^2 R^2$$

If we rearrange to solve for rotation rate we get the equation:

$$\omega = \sqrt{\frac{8\sigma_t}{(3+\nu)\rho R^2}}$$

Using:

$$\nu_{Steel} = .3$$

$$R = 1980km = 1.98x10^6 meters$$

$$\sigma_{Steel\ with\ Safety\ Factor} = 200MPa = 2x10^8\ Pa$$

$$\rho_{Steel} = 7850\ kg/m^3$$

Solving for ω we get 1.255x 10^{-4} rad/s which works out to .0012rpm or one rotation ever 834 minutes- or about one revolution every 14 hours.

With the planned Starship Launch payload of 150mt and goal of $100kg, we would require 821,000 launches at a total cost of 12.315 trillion dollars! Note that this is unrealistic as the world GDP in 2021 was on the order of $100 trillion. Nevertheless in 2019 there were about 38.9 million commercial flights worldwide (Statista Reasearch Department, 2023) so it is not impossible to envision that over the next few decades that the number of rocket launches will grow significantly. If, as with the SBSP scenario, we drop launch costs by $10kg every 1900 launches, we will reach our target cost of $50kg very quickly and early on in the program.

To the cost of launches, we would add the cost of development. The solar Occulus is fairly low tech (compared to the SBSP system) so I assigned a cost of $10billion.

Finally, the manufacturing cost of the Occulus needs to be considered. As opposed to the solar power facility, I originally proposed that the simpler design of the Occulus should lead to a much lower initial cost- 1/10th the SBSP manufacturing costs per kg or about $10kg. For comparison, a typical 2mt $50,000 car costs $25/kg. Furthermore, with increased manufacturing efficiencies as thousands of square kilometers of the Occulus are built, manufacturing prices would likely drop further- to a final estimated $5kg.

Total Reduction	Launch Costs $B/mt	Development Cost $B	Manufacturing Costs $B	Cost per incremental .1%	Total Cost
0.10%	278	10	28	316	316
0.20%	278	0	28	306	621

Table 12-7 Occulus Costs costs for initial .1% increments; launch and manufacturing costs are assumed to quikly be reduced during the first increment to $50kg for launch and $5kg for manufacturing, and with the intial development costs hitting the first .1% increment

We can compare the costs of various Occulus configurations in Table 0-3 to the SBSP satellites of various sizes shown in Table 0-1. For the SBSP station I reduced manufacturing and launch costs for every 1900 launches. Because of the sheer number of launches needed for the Occulus, I use the mature launch and manufacturing costs right at the start- $50kg for launch and $5kg manufacturing. The Occulus, since it is scalable, will start out relatively small- and intercept only .1% of the radiation. The first .1% Occulator will cost $316 billion, and each follow up unit $306billion. To build an occulator that intercepts a full 2% of solar energy would cost 6.123 trillion. I believe that this would be achievable if spread out over a 20-year implementation plan of about $310 billion per year.

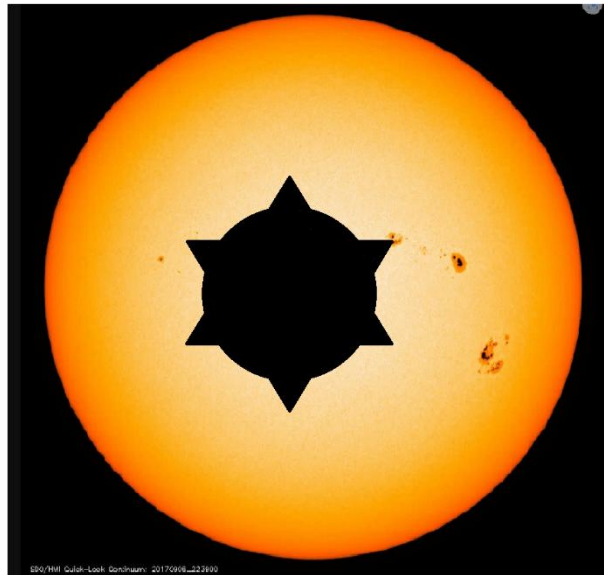


Figure 12-10 Occulus transiting the Sun as seen from near the equator and near noon. Note the triangular vanes used for tacking and manuevering.

The primary cost driver for a relatively low-tech solution like the Solar Occulus is its huge mass and associated launch costs. If we could significantly lighten the Occulus with a mass of only 5g/m2 we would half our costs. Furthermore, it may be possible to reduce launch costs even further- by supplying the required materials from the moon and launching them with a mass driver. Unfortunately, some of the raw materials that might be considered for the Occulus are various carbon rich fibers and the moon is extremely poor in carbon. Depending on the infrastructure being built on the moon, it may be possible to build a much heavier Occulus and still be much cheaper than suppling materials from earth. If we built a large mass driver, we could launch vast quantities of material for just the cost of the electricity. If launch costs are so low we could build the Occulus out of lunar sourced Aluminum or Titanium sheets.

Note that when comparing alternatives, cheaper launch costs would similarly lower the cost of a SPSP system. However, with the SPSP system less than half the total costs are related to launch prices whereas over 90% of the Occulus costs are. Similarly, if the manufacturing cost of the SBSP were higher than $100kg but the Occulus costs achieved their target of $5kg, this would shift cost benefits to the Occulus sooner.

Despite the high cost, it may still be advantageous to build an Occulus. The Occulus is scalable- we may start out with one that intercepts only .1% of the solar flux. We could gradually expand it over several decades as needed and as other technologies evolve that reduce greenhouse gas emissions. As mentioned, expanding it to 2% would negate the next one hundred years of temperature increases, buying additional time to develop SBSP, and Fusion/Fission. One way of looking at it is that the cost of a $6 trillion Occulus is equivalent to building 2070 GW_e of SBSPs (or about 10 years of projected worldwide annual growth in electricity usage) but buys us one hundred years of time!

Alternate Designs

The proposed design has the simplicity of a single large structure able to be adjusted and moved as needed to vary the desired effect. Alternate designs are available that may be preferred. However, for several reasons I doubt that this would be an acceptable solution.

The simplest alternate design is to place multiple large "Occulators" closer to the earth that block the sun's rays periodically. These could be placed in any orbit but be easiest to maintain would likely be a geosynchronous one. Since this orbit is only 1/42nd as far as L1 our Occulus would only need to be about 1/42nd the diameter for the same amount of shade and its area only about 6301 km^2. This area would work out to only about 1/764th the size of our L1 Occulator. Unfortunately, at this distance from the earth the Occulator satellite would transit the sun in only about 2 minutes. To keep a continuous progression of such transits, we would need a total of about 720 satellites in a circular band around the earth- negating a substantial portion of the size advantage.

We could even consider building a line of these stations connected into a continuous large band that would girdle the earth- a configuration that would look like a ring around the planet- though because of its orientation the thick part would be along its axis so it would bear some resemblance to a ringworld. The stability of such a system would be difficult to maintain as the incoming solar radiation pressure as well as the gravitational effects of the moon would tend to push these around and distort the ring and possibly tear the structure unless we engage in continuous active adjustment. All of these alternate designs are dynamically much more complicated and not as mass efficient as you would imagine… only a portion of the band or a few of the large orbiting shields would actually be intercepting the sunlight headed for the earth at any particular time. Perhaps even more importantly, these hundreds of large shades or this ring would be visible at night, each brighter than the full moon. Nighttime would be effectively eliminated- not a very green solution.

Occulus Design, Station Keeping, Orientation and Positioning

Effectively the Occulus will be a large (though poorly performing) solar sail. Like a solar sail, it will have various moveable flaps or panels for attitude adjustments (see Fig 0-13) and will be maneuverable enough for station keeping as the L1 point is not completely stable especially because of the effects of the moon's gravity. It may be cost effective to build several large sections of the Occulus in earth orbit and then, using their intrinsic solar sail capabilities, gradually raise their orbit until they get to the L1 point.

The proposed Occulus would be positioned just inside the L1 point nearer the sun where the suns gravitational and solar radiation pressure will be balanced by the earth/moon gravitational forces. Keeping the Occulus in the correct position will require continuous orbital correction achieved by light pressure from the sun (as with a solar sail) with large moveable flaps that can be extended or retracted so as to give the appropriate orientation and course correction.

To determine the Occulus performance and material temperature we will assume a reflectivity of 80%. Using the equation for the force a solar sail generates we have the equation:

$$\boldsymbol{F_{Sail}} = \frac{(\mathbf{1}+\boldsymbol{k})\boldsymbol{I}}{\boldsymbol{c}}$$

Where:

k: Sail reflectivity between 0 and 1. A perfectly reflective sail would be 1.

I: Intensity per m2. On earth this is about 1366w/m2. At the L1 point it would be slightly more- 1408w/m2.

Filling in for c, and setting k=.8 we calculate:

F=.0000085 newtons per m^2

This force from the sun would counteract the net gravitational forces that our solar sail would experience since it is just inside the L1 point.

To calculate the temperature of our Occulus we need to use the following equation:

Equation 12-2 $L_\odot = 4\pi R_\odot^2 \sigma T_\odot^4$

Where:

$L_\odot$ is the suns luminosity.

σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4)

$R_\odot$ is the radius of the sun in meters. This is 696 x 10^6 m

$T_\odot$ is the temperature of the sun in Kelvin. The surface temperature of the sun at $R_\odot$ is 5780K

To determine the temperature at a different distance from the sun we can use the equation:

Equation 12-3 $T_T^4 = (\frac{R_\odot^2 T_\odot^4}{4R_T^2})$

Where T_T = temperature of our Target and R_t is the radial distance to our target.

Rearranging and simplifying:

Equation 12-4 $T_T = T_\odot\sqrt{(\frac{R_\odot}{2R_T})}$

For our Solar Occulus at L1 R_T distance from the sun will be about 148,500,000 km. Substituting

$$T_T = 5780K\sqrt{(\frac{6.96x10^8}{2 * 1.485x10^{11}})}$$

T_T= 279.8K

We are actually even cooler than this. If we assume 80% reflectivity (20% absorption) we have:

$(.2)^{.25} = .56$

or only 56% of the temperature. Our Occulus temperature will now be only 157.33K. The temperature will not be a problem.

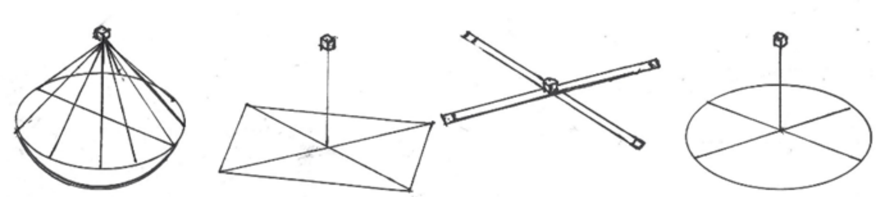


Figure 12-11 Similar in design to Solar Sails, here are some possible Occulus configurations.

The Occulus could be built in many configurations similar to the designs for large solar sails. It would likely be a tension structure where the tension is caused by a slow rotation rate- perhaps on the order of once every 10 hours. The benefit of the Occulus over a solar sail is that its performance is mass independent. As opposed to a solar sail that needs to be large but feather light to achieve high performance, our Occulus does not need to be exceptionally light. The only reason mass is important is the substantial costs associated with earth launch or launching the required material from the moon with a mass or momentum driver delivering the mass to L1.

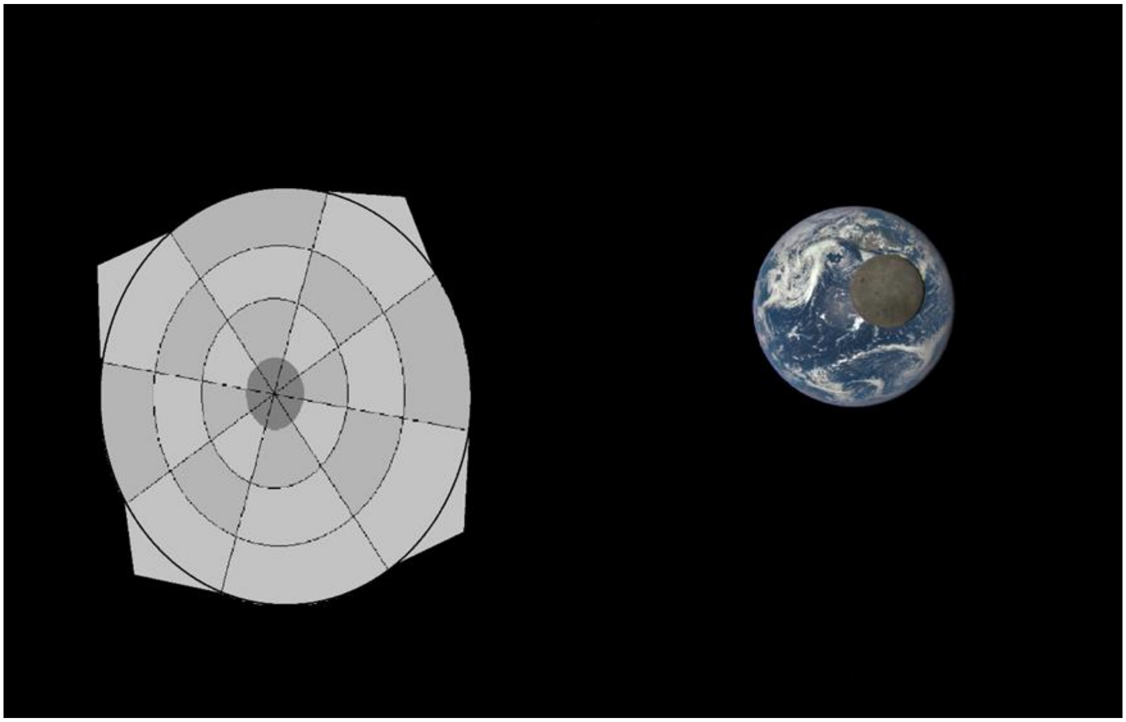


Figure 12-12 The Occulus 1.5million km in front of the Earth/Moon system

Advantages and Disadvantages of an Occulus Station over a Geosynchronous Power Station

The Occulus has several advantages over a Geosynchronous Power Station:

- Much lighter per square meter.
- Much simpler design, manufacture and assemble. Low Tech. Most of the mass will be a thin, lightweight material or fabric in tension.
- Cheaper (per m^2 and kg of mass) to build due to its simple design.
- Low risk- no new technology and simpler logistically. Even though the engineering of physics of large Solar Power stations is well known, the construction of such massive stations with Gigawatts of power that also can beam down this power via Microwaves is a substantial, though achievable, technological challenge. The Occulus is a lightweight membrane stretched out over many kilometers and can be designed with minimal engineering.
- Scalable. The Occulus, as currently proposed, can, through appropriate positioning, intercept anywhere from 0%-2% of the solar radiation. By nature of its design, it can be enlarged or shrunk as needed.
- Requires no land for power receiver.
- Can easily offset global warming anticipated over the next one hundred years.

These advantages mean that the Occulus could be designed, built, and launched relatively quickly as long as space launch capabilities are expanded, and launch costs decrease to $100kg or lower. It is not much of an extrapolation to believe these capabilities will be achieved within the next decade.

The disadvantages of an Occulus that blocks 2% of the sun's energy over SBSPs plant are:

- Much higher total mass and therefore much higher launch costs
- Even though the Occulus is much lighter per square meter than the SBSP facility, the area is so much larger that the total manufacturing costs will likely be higher.
- Unlike the SBSP it does not generate any revenue. For the price of a $6 trillion Solar Occulus, you could build the equivalent of more than 200 10GWe SPSP plants that would collectively generate (at 16.2cents per kWh) $2.8 trillion in electricity per year.
- The Occulus does not reduce Greenhouse gas emissions.

Additional Uses for an Occulus

The Occulus and its associated technology have even more exciting applications further into the future. An exceptionally large Occulus placed at the Venusian L1 point could make this planet habitable- though it would need to be much larger in order to block most or all of the sunlight to quickly lower the planet's temperature. Extremely massive quantities of hydrogen would be imported to convert a portion of the CO2 atmosphere into water and large quantities of carbon (note some of the carbon may be useable to build the Solar Occulus).

Summary of Alternatives

Determining the actual costs to build and operate these various power alternatives is difficult and outside the scope of this book. Part of the reason for this is that certain tax and rule advantages are in place in many countries to encourage certain energy resources and discourage others. Nuclear in particular has been restricted in construction due to hostile regulations and low rate of production (i.e., in the US only one new power plant is currently under construction). This will tend to drive the cost of Nuclear Power higher. Furthermore, nuclear reprocessing and breeder facilities have been shut down for political reasons, further driving up costs. Conversely, there are favorable rules and tax breaks in place to encourage wind and solar development. The rapid expansion of these technologies has reduced their apparent prices to the customer. However, since these are artificial price distortions, they are subject to changing policies and do not reflect the true costs. Because of this I have concentrated on only some broad aspects of the characteristics of the various energy sources in Table 0-4 and the engineering challenges of building 450GW_e Worldwide of green power each year. Changing the Earths Albedo and the Solar Occulus do not address increased CO2 emissions nor power requirements and have no cash flow so are not included in this table.

Source	Plant Size	Number Needed	Comments
Nuclear Power	1 GW	450 Nuclear Reactors	Least Emissions, Least Land. Most regulated. Large potential for economies of scale. Most Nuclear plants consist of 2-3 Reactors of 1 GWe each.
Renewables			
Bio Diesel			Not likely or practical. Frequently create more greenhouse gases than they prevent. Will be useful for aircraft and vehicles.
Solar	75 W_e/m2	6000km^2 per year	Land intensive if dedicated power plant. No inexpensive solution to power storage. Distributed rooftop installation will use less land, but costs are several times higher

Wind	2 MW_e Average	225,000 turbines per year	Larger Turbines can be installed at sea and can reduce this quantity by 50%. Sea installation and maintenance costs will be higher. No inexpensive solution to power storage.
Hydroelectric	2.5 GW_e Average	180 Dams per year	Not many undeveloped large rivers remain. Environmental regulations make new dam construction difficult to get approved.
Space Based Solar	286 W_e/m^2; 250 W_e/m^2 Ground	45 10GW facilities per year requiring a total of 1573km^2 space 1800km^2 ground	Space based area and ground receiver-based area. Substantial and efficient launch capabilities required.

Table 12-8 Requirements to build 450GWe per year

Summary and Conclusions

Terraforming the Earth is occurring now. Large portions of the planet that were traditionally arid are now irrigated and crops grow in many marginal areas. Large dams are constructed for flood control and power generation with large manmade lakes a byproduct. Even more fundamental is the inadvertent release of large quantities of CO2 which is increasing the earth's temperature.

Space may also directly aid civilization and further influence the Earth in the future. Large SBSP stations could provide a meaningful contribution to civilization's energy needs. I suspect that several moderate to large (1MW-10MW) SBSP stations will be constructed over the next hundred years but their high costs, along with the pollution (CO2) emitted by their launch, will make them a secondary source to earth based Nuclear power. An additional area of growth may also be building SBSP that are part of orbital data centers. Regardless it seems certain that some sizeable earth orbiting solar power stations will be built- either to provide energy to the Earth or to remove some power hungry data centers and place them in orbit.

I don't believe that there will be a solar Occulus built for modification to the Earth's temperature. However the technology will be very useful helpful in modifying and terraforming Mercury, Venus, and Mars, as well as having some technological overlap with Solar Sails.

Chapter 13 - Terraforming the Moon

In the first 11 Chapters we discussed the resources, scale and logistics of space colonization over the next 100 years. With Chapter 12 we investigated larger projects to including very large solar power facilities and making modifications to the Earths radiation budget to address global warming. The Solar Occulus discussed in Chapter 10, while large, was also well within the capabilities of a modest space based civilization over the next 100 years.

In the next few chapters, we will get much more speculative- we will look at terraforming projects that require vastly more power and resources, and in many cases, millennia to execute. In many cases the power and resources required will be orders of magnitude more than the entire productivity of the whole earth. These Chapters will mainly serve as a reality check on the more enthusiastic ideas sometimes displayed in popular culture. Except for a modest terraforming of Mars (Chapter 14), all other terraforming will likely be centuries in the future before they can even be considered. In Table 1-3 we showed the tremendous increase in human economic power over the last 50 years. During that time economic power increased by about 4x. If this rate of change were to continue, in 100 years our economic capacity would be 16x greater. In 200 years our capabilities would be 256x greater.

A civilization that has economically grown by 256x, will find terraforming more reasonable- if impractical. Terraforming may indeed be impractical and unworkable… most of the bodies that would be considered, the Moon, Mars, Mercury, Titan, have much lower gravities, severely limiting how Earth like they can be made. It is for this reason, as we shall see in our analysis in the following chapters, there are limits to what we will likely want to accomplish. Ranking the top five terraforming objectives in order of likelihood:

- Mars- mild terraforming- likely; major terraforming- possible
- Venus- Major; possible
- Mercury- Major; unlikely
- Moon- Major; unlikely
- Titan- Major; unlikely

These are the prime candidates for terraforming- other bodies are even less likely. In Chapter 16 we will look at terraforming of some of the outer planets satellites but in all these cases, terraforming is likely not worth it. We will also look at the possibility of building "Cloud Cities" on Uranus and Neptune, which will turn out to be more practical than terraforming.

In Chapter 17 we will look at the extremely difficult prospect of building an Earthlike planet from scratch. This would be a project more suitable for a civilization 300 or more years in the future.

Even though I feel that these next chapters are unrealistic and may never be done, I included them both for information, but also because of Table 1-3. This may be the most important table in the book, for it shows the power of compounding. Extrapolating current trends almost never leads to a realistic outcome- the tremendous growth in GDP and Power usage seen likely be different than what we observed over the last fifty. Growth may slow significantly. However, the opposite may happen - growth can easily exceed the historical change rates. The growth of AI, if harnessed with robots, may dramatically accelerate the need for power as well as our economic productivity. Low-cost space based solar could drastically increase our electricity supply. If we increase our power usage by 3% per year worldwide we would double our energy generation in about 23 years- a large but not unreasonable increase. But if this trend were maintained, over 100 years the energy generation would go up about 20x. Over 300 years energy generation would be 400x greater than now!

Terraforming of the Moon

The moon, because of its proximity to the Earth, is in some ways, the most logical body to terraform. There are however, some very large disadvantages and difficulties to lunar terraforming.

Facts About the Moon- Geology

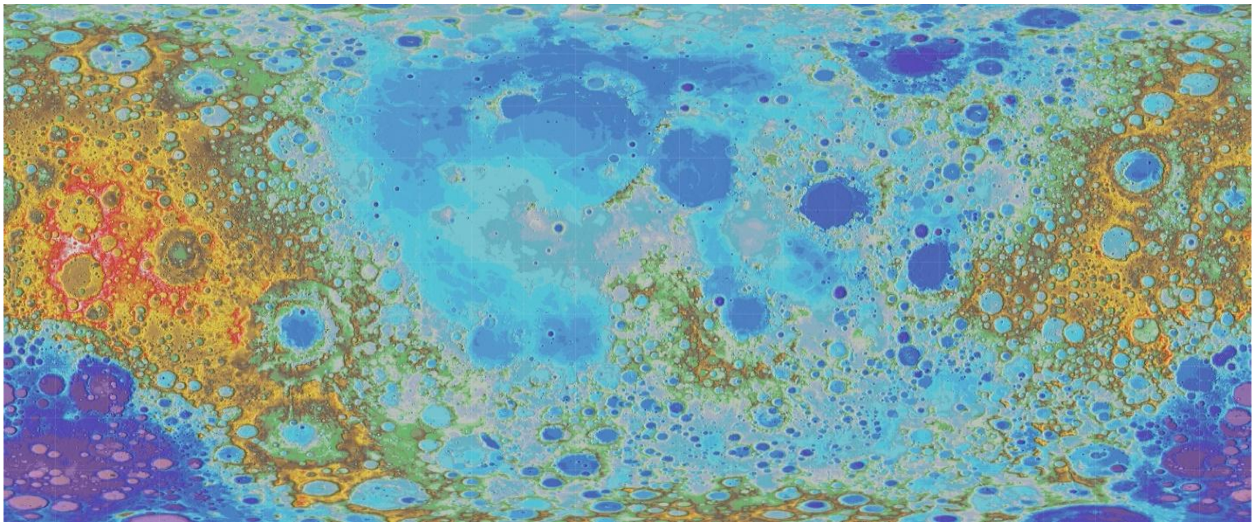


Figure 13-1Moon Fact Sheet (nasa.gov)

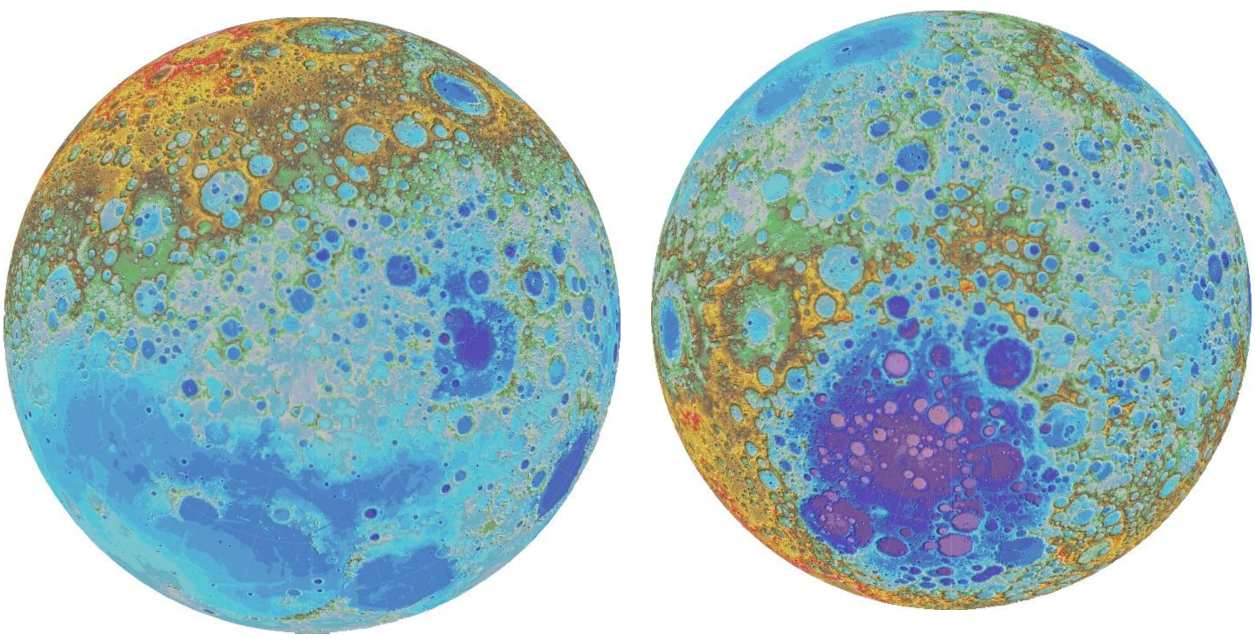
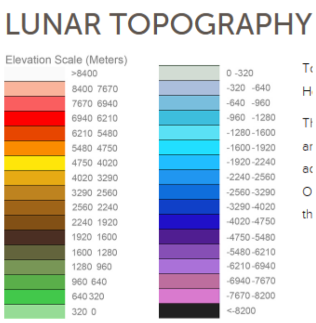


Figure 13-2



Positive Characteristics of a Terraformed moon.

The goal of a terraformed moon is ultimately to permit humans, plants and animals to exist on the surface with no or minimal protection. As such, a sufficiently dense atmosphere with sufficient oxygen for respiration would be required. Implicit with this would be sufficient water for the growth of plant life. Furthermore, a more amenable day night cycle much closer to earths would be needed for both growing conditions and to eliminate wild temperature swings.

Terraforming of the moon would permit a very large population and self-sufficient colony. At the very least even a low-density population could number in the tens of millions. The Earth has an average population for all land area (including Antarctica) of about 50 people per km^2, which if we applied to the moon with a surface area of $3.793x10^7$ km equates to a total lunar population of almost 1.9 billion.

The first requirement of a terraformed moon would be to provide a earth equivalent atmosphere- of similar pressure and consistency with that of the earth. Terraforming would permit the growing off crops, forests, animals, and birds. The low gravity would permit organisms to become very large. Trees that are limited in growth due to gravity and the transportation of water to the upper most branches could in theory grow six times taller- though other factors may prevent this. The size of animals are limited genetically from growing too large, but this limit was also driven by their evolution in earth gravity. Reducing this gravity by 85% would permit, if genetically modified, very large animals including birds.

A terraformed moon would have very small tides that would wax and wane twice every 28 days or so if the moon's rotation rate were not adjusted. The tides would primarily be driven by the sun, however some amplifying effects would occur from the earth as the moon's orbit is not circular around the earth.

The surface of a terraformed moon would have less cosmic radiation than is experienced on the surface of the earth. The low gravity of the moon means the atmosphere would extend much further out than on the earth and be much more massive for any given area of the surface. To get the equivalent sea level pressure as on earth would require six times more atmosphere per unit of land. This extra thick atmosphere would block almost all cosmic rays and more than offset the lack of a lunar magnetic field.

A terraformed moon would eliminate the threat from smaller meteors. Any meteorite less than a few hundred kg would burn up. As with cosmic radiation, a terraformed moon would have greater meteor protection than the earths surface because of the much more extensive atmosphere.

A terraformed moon would permit approaching spacecraft to aerobrake for landing- conserving fuel for landing. However, it now would require a spacecraft to have aerodynamic surfaces and require a stronger and heat-resistant structure.

Challenges with Terraforming the Moon

The challenges to terraforming are significant. The moon will rapidly lose any atmosphere due to its low gravity and escape velocity (Figure 0-3). The only element that is heavy enough not to rapidly get stripped off is Xenon- which is a minor atmospheric component on earth. If the moon were terraformed this would permit spacecraft to use atmospheric braking to slow down and land but it also means that nothing could orbit the moon below tens of thousands of kilometers.

Water in the upper atmosphere will be subject to high solar radiation that will separate into oxygen and hydrogen. Both will quickly leave the moons low gravity. How quickly the atmosphere will be lost depends on its density and composition, and imperfect models of atmospheric escape give a large range of values, but at a minimum, hundreds of tons will be lost per hour.

How much atmosphere would the moon need? The moon has a surface area only 7.64% of the earths. However, to achieve the same atmospheric pressure as that of earth, six times more atmosphere is required per square kilometer. This means that the total mass of the moon's atmosphere would need to be about 46% of the earths! This is a lot of nitrogen and oxygen.

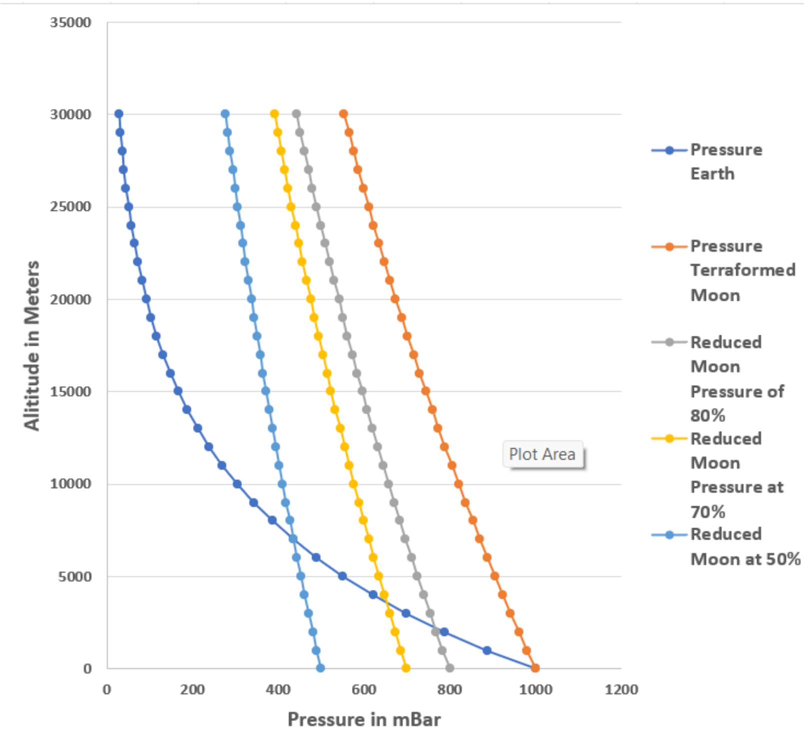


Figure 13-3 Atmospheric Column Pressure vs Altitude comparing Earth pressure with lunar pressures at 1000mBar, 800mBar, 500mBar and 800mBar

In addition, the slow rotation of the moon will provide extreme difficulties to making the lunar surface comfortable. Even though the atmosphere will mitigate the effects to some extent, two weeks of sunlight will make daytime highly uncomfortable- depending on cloud cover, your altitude and other weather conditions, it is likely that temperatures would be north of 150F. Similarly, on the night side, two weeks of dark will likely lower the temperature to below -100F. I may however be unnecessarily pessimistic as the mass of the atmosphere is much greater per each meter of surface area compared to the earth, and this, combined with large heat sinks like large lakes and oceans, will dampen out the swings. Parts of the earth, during the winter season, experience months of little or no sun. These places become extremely cold, and some are uninhabitable, but others, near moderating oceans and not exposed to months without sun, do support life, including trees and animals.

What the slow rotation means is that we only have two weeks at a time to do our crop growing. and make growing of almost all plants extremely challenging. Plants will not have months to grow but only a couple of weeks of continuous daylight, a portion of the time being under extremely high temperatures. Then they will go without sun for two weeks while being subject to below zero temperatures. Most plants will die, though I would imagine some trees and slower growing plants could handle the cycles. A further factor to consider is that depending on the mass of the atmosphere we selected our atmospheric column will be much thicker than on earth. If we shoot for an Earth like pressure atmosphere, with the substantially 6x more massive atmosphere per kilometer, solar rays would have to travel through six times more atmosphere before reaching the ground so that sunlight would be weaker and much more attenuated.

These huge temperature fluctuations between day and night will result in huge atmospheric movements which could help keep temperature extremes less than would be expected. High winds will likely follow the terminator. On the daylight side, hot air will expand and rise up and push into the cold side from the upper atmosphere, while the colder, denser air on the night side will sink and then slide across the terminator toward the daylight side with extremely high winds. The hot air that travels to the night side will quickly drop in temperature and the water and any carbon dioxide will freeze out with astronomical amounts of snow.

A detailed analysis of the moon's weather will have to be done, but a lot depends on the target atmospheric pressure. However, based on our analysis throughout this book, I believe we could operate with a much lower atmospheric pressure than that on the earth. Other than serving as a larger buffer for temperature swings, there is not much of an advantage to an earthlike pressure. The low lunar gravity means that even with a reduced pressure, flying (whether birds or planes) will still be possible. Low gravity reduces the stress on organisms and less oxygen is needed. My initial thoughts are that an atmospheric "sea level" pressure of only about 700 mbar is adequate. Oxygen levels can be tweaked up to 25% to offset the effects of lower pressure.

It may be determined that a day/night cycle of 28 days is unacceptable for a terraformed moon. Other engineered solutions could partially address this. During the lunar day a 24 hour artificial day/night cycle could be done with an dual disk Occulus or an Occulus with shutters. However, if only the daylight issue was addressed, this could make growing plants even more of a challenge. Sunlight will now only be available for about 7 days out of a 28-day cycle. A much more challenging solution would be to build another structure, a highly reflective mirror like second Occulus that would shine light down on the dark side of the moon. However, the orbital path that this would have to follow is very complicated and would have to be constantly adjusted. Furthermore, this mirror would only be shining down for 12 hours a day, at which time the reflected sunlight would then be directed elsewhere, which introduces a large amount of additional complexity.

These conditions could be ameliorated if the moon's rotation were sped up to more closely equal the earth's. However, we will see later in this chapter how impractical this would be.

Atmospheric loss mechanisms

Mars lost much of its atmosphere in its first half a billion years or so of its existence. The moon will not be so lucky for several reasons:

- Its gravity is only about half that of Mars. Because of its low gravity its atmosphere will distend far higher than the early Martian atmosphere or the earths current atmosphere. This distended atmosphere and low gravity means that the moon will lose its atmosphere much faster than Mars. If the moon were given an "sea-level" atmosphere only 80% that of the earths, at 100km its pressure would be equivalent to the earths at about 19km. In the next section I will review how this is calculated.
- The moon has no magnetic field to deflect charged particles from the sun. Charged particles may help strip away an atmosphere (though recent studies cast this in doubt).
- The moon is much closer to the sun than Mars and receives about 60% more energy. This tends to inflate the atmosphere even more and, combined with the higher temperature of the atmosphere, allow it to be stripped more quickly than at Mars.

A planet or moon can lose its atmosphere primarily due to two mechanisms- thermal, non-thermal and impact erosion.

Thermal escape are primarily through two means:

- Jean's escape
- Hydrodynamic escape

Non-Thermal escape includes:

- Photochemical escape
- Sputtering Escape
- Charge Exchange Escape
- Polar Wind escape.

Finally, we have impact erosion. For our purposes, this is not likely to be an important consideration for the near and midterm.

Lunar Rotation Increase

One partial solution to several of the issues with Lunar habitability could be solved by increasing the lunar rotation so that a lunar day was closer to that of earth- 24 hours. This would mitigate several issues with terraforming:

- Growth of plants
- Improved and stabilized weather
- Possible generation of a magnetic field which would slow atmospheric losses

However, the amount of energy required to increase the moon's rotational speed is truly astronomical and would involve the vaporization of its surface. We can determine the amount of energy required by comparing its current rotational energy with that of an accelerated moon by using the equation:

Equation 13-1 $k = \frac{1}{2} I\omega^2$

The equation for rotational inertia for a uniform body is:

EQUATION 13-2 $I = \frac{2}{5} mr^2$

Since the moon is not a uniform body we would use the number 0.3929 in lieu of the 2/5.

Using equation 16-3 the Inertia of the moon can be calculated as 8.807×10^{34}kg/m^2.

The current angular velocity of the moon is 4.1336×10^{-7}rad/sec

Plugging this into our equation for energy we get 7.524×10^{21} joules.

The proposed rotational rate will be 28 times faster or 1.1574×10^{-5}. The difference between these two represents how much energy it will take to accelerate the moon and works out to be 5.891×10^{24}joules. A very large 10Megton nuclear weapon releases about 40,000 TJ or 4×10^{16} Joules which means you would need some 147million nuclear bombs worth of energy.

The total incoming solar energy on the earth is 173,000TW or 1.7x10^{17} watts. The moon surface area is only 7.4% of the earths meaning it receives the equivalent of 1.258x10^{16} watts. The energy to accelerate the moon is the equivalent of all the energy that strikes the moon over about 14.8 years. The problem with applying this much energy to the moon over a few decades is that it will cause substantial heating of the lunar body, causing large scale volcanism and earthquakes. As opposed to most of the energy that hits the surface and gets reradiated back out at night, spinning the moon would primarily involve adding this energy to the internal structure. This heat would build up and substantially heat the inside. Furthermore this amount of energy is far more than humans have ever created or harnessed.

An alternative to accelerating the moons rotation a more reasonable solution may be to build a large solar occultating shade to block sunlight every 12 hours for the sunward facing hemisphere. This however would answer only part of our problem. The dark side would be exposed to 14 days of continuous night so a large solar mirror to that illuminated the moon for 12 hour stretches would also need to be built and positioned on the opposite side of the moon.

The darks side would need a large solar mirror to provide 12 hours of daylight to the part of the moon. An object that orbits the moon in a 24 hour orbit needs to be about 42,400 km from the moons' center of gravity. Conversely a single shade could fully block the suns light for about 12 hours, but as it rotated around the moons dark side, it could reflect light towards the "darkside" of the moon. This shade would be an extremely challenging structure to build as it would have the appearance of a huge, 180deg arc. Orbiting this far from the moon, the structure would be subject to large tidal forces from the earth, and to a lessor extent, the sun. They would need to be actively steered, likely be solar radiation pressure.

A Lunar Occulus and Mirror

There are several things that can be done to help terraform the moon, though few, if any, will actually make sense. The simplest thing would be to install a blocking occulus and a reflecting mirrors on opposite sides of the moon in order to get an appropriate day/night cycle.

To give the moon a normal day/night cycle we might position a large occulus between the moon and sun, with an iris or shutters that would open and close every 12 hours. The problem is that the occulus would need to orbit the moon once every 29.53 days and this point is about 88,000km. This is outside 60,000km which is the so called Hill sphere- the area where the moon's gravity dominates over the earth. At 88,000km the Earths gravity will quickly pull the occulus out of orbit.

	Position	Size (diameter)	Comments
L1 (Shade)	88,000 km inside Moon	≈11000km	100% Shade with Panels or Iris
L2 (Reflecting Mirror)	88,000 km outside Sun/Moon	≈3000km	Assume 90% reflectivity; goal 650W/m2 light to Mercury

Table 13-1

Because of these constraints, an Occulus and Mirror at L1 and L2 would not be possible. Alternatively we could build a chain of mirrors or shades that rotate over a 24 hour period. This would orbit about 10,000km above the lunar surface. However, a shade a little larger than the moon would provide only a few minutes of total darkness- it would travel about 1deg/min across the sky.

A compromise might be a shade orbiting slow enough to provide 12 hours of darkness because of its orbit and not a fixed sun-moon shade that opens up an iris or panels to admit light. A 400km wide, but several thousand kilometer tall (north/south) orbiting at 40,000km could give a day night cycle to any point- but it would be in a narrow slow moving band across the moon. Multiple bands would need to be orbiting the moon so that a bunch of slowly moving shadow strips would give you a normal day/night cycle. However this will also be extremely inconvenient as essentially every few hundred kilometers across the moon would be a different day.

Bottom line is even imposing a normal day/night cycle on the moon will be very difficult. Add to this difficulty is the tremendous volume of volatiles (nitrogen, oxygen and water) that would need to be added, combined with the low gravity (which we can't change) and building several alternating shades and reflectors, and importing gigatons worth of volatiles, means terraforming the moon is impractical.

The Steel Moon

Are there ways to make a terraformed moon possible that address these concerns? There is, though the solutions themselves present additional difficulties.

What happens if we were to enclose the moon in a steel spherical pressure vessel? Essentially a steel (or aluminum or titanium) roof would be constructed around the moon, several kilometers above the moons natural surface that would be supported by the atmospheric pressure below.

At first glance this seems absurd. Indeed, the requirement for building a steel roof, as with any terraforming, are far beyond current industrial capabilities. However, there are multiple advantages that will likely make this the only way to make terraforming the moon possible- if and when a decision is ever made to terraform.

- Depending on the height above the ground of the roof the amount of atmosphere required will be substantially reduced- easily less than half and perhaps as much as 75% less than that required for a normally terraformed moon.
- Atmospheric loss will become essentially non-existent.
- The artificial roof will insulate the lunar surface from the 14 day day/night cycle making the temperature and weather extremes much less.
- The light beneath the roof can be adjusted so that a normal 24 hour cycle is followed. This can be done either exclusively with artificial lighting, or natural sunlight beamed around to the dark side, or a combination of both.
- There would be no need to construct a planet wide magnetic field to help protect the atmosphere from escape (though this may not be a requirement anyway).
- Spaceships will be able to orbit the moon as they currently do, without having to stay many thousands of kilometers to avoid atmospheric drag.
- To make the roof practical, the metal roof will be covered with lunar regolith providing both cosmic ray and meteor protection.

Operating Parameters and Design

One of the first items to be aware of is that there are no materials strong enough to create a spherical body under pressure that is the size of the moon. A simple equation to determine the stress of a pressurized sphere from Equation 9-4 was:

$$\sigma_p = \frac{pr}{2t}$$

There is a simple and effective way around this constraint- build a pressurized roof but put lunar regolith on top so that the roof weight exactly offsets the atmospheric pressure below. The roof will be in equilibrium and under no stress and will essentially float.

We have several issues when designing our lunar steel roof and will need to identify the parameters of our design. We need to make the following determinations:

- What is the target atmospheric pressure at "sea level"?
- What are the environmental constraints below the roof- temperature, humidity, atmospheric turbulence?
- How high does the roof need to be?
- What will the roof be made of and how thick will the structure be?
- How will the roof operate? The following will be items that need to be considered in the design:
    - Thickness of roof structural material
    - Thickness of lunar regolith piled on top of our roof
    - Attachment to the surface
    - Temperature and light regulation
- What raw materials for the roof, as well as the atmosphere and terraforming requirements, will be needed?
- Where will the raw materials be sourced and how will they be transported and delivered?
- We will need to design a roof that is durable enough to withstand punctures from meteorites or errant spaceship crashes. If punctured the damage will need to be controlled and limited
- The utility infrastructure requirements of the roof will need to be identified. These include
    - Solar power
    - Temperature control
    - Lighting and Electric
    - Spaceports and lunar elevators
- A process and equipment will need to be identified and the process for building the roof will need to be developed.

Identifying a Target Atmospheric Pressure and roof parameters

Atmospheric pressure varies with height, gravity and temperature. The closer to a surface with gravity, the greater amount of atmosphere is piled on top, creating a higher pressure as you reduce altitude. There are a couple of ways to do calculate the pressure at a particular altitude:

Equation 13-3 $P = P_b[\frac{T_b+(h-h_b)L_b}{T_b}]^{\frac{-g_0 M}{R^4 L_b}}$

Where:

$$P_b = reference\ pressure$$

$$T_b = reference\ temperature\ (K)$$

$$L_b = termperature\ lapse\ rate\ (K/m) in\ ISA$$

$$h = height\ at\ which\ pressure\ is\ calculated$$

$$h_b = height\ of\ reference\ level\ b\ (meters)$$

$$R^* = universal\ gas\ constant: 8.3144598\ {}^{J}/_{(mol\ K)}$$

$$g_0 = gravitational\ acceleration: 9.81\ {}^{m}/_{s^2}$$

$$M = molar\ mass\ of\ Earth's\ air: 0.0289644\ kg/mol$$

This is the more accurate calculation as it includes the variation of Temperature with altitude (lapse rate). Equation 13-4 assumes that temperature remains constant and as such is simpler but less accurate.

Equation 13-4 $P = P_b e^{\left[\frac{-g_0 M(h-h_b)}{R^* T_b}\right]}$

Due to the simpler design of the moons' atmosphere, and the fact that there are many unknowns about our final design, I will use the simpler equation. Both equations lead to similar curves so the loss of fidelity is not very important. If we set the reference height for Equation 13-4 to zero (sea level) we simplify the equation to:

Equation 13-5 $P_h = P_o e^{\frac{-mgh}{kT}}$

Where:

k= Boltzmann's constant (ideal gas constant divided by Avogrado's number)

For temperature I used 287K or 14C since this is the average temperature of the earth. I assumed we would target the same temperature for the moon.

The highest elevation on the moon is about 18000 m above mean datum. We will make our roof 20km above the mean to clear all mountains. However, the lowest point on the moon is about -8000meter which would make the vertical distance from low to high some 26 km.

Initially we will select a pressure 80% earth sea level as our pressure as the mean – equivalent to the pressure at about 2000m. I can think of no advantages to increasing the pressure above this. Furthermore, if the pressure could be reduced further it would reduce both the amount of gas that needs to be imported as well as the mass of regolith that would be stacked on top of the roof. We will look at the impact of various pressures with both the magnitude of the gas needed, as well as the thickness of the regolith. There are however limitations below which we would not want to go.

Figure 0-4 shows a graph of the resulting calculations. In it I show pressure on the earth vs pressure on the moon at the sea level values- of 1000mbar, 800mbar, and 500mbar pressure. It becomes immediately clear that the lower gravity on the moon leads to the atmosphere distending or puffing out. I also show a line that assumes a mean lunar pressure at 800mbar with a steel roof. Essentially the atmosphere above the roof is eliminated saving the need to import this volume of gas.

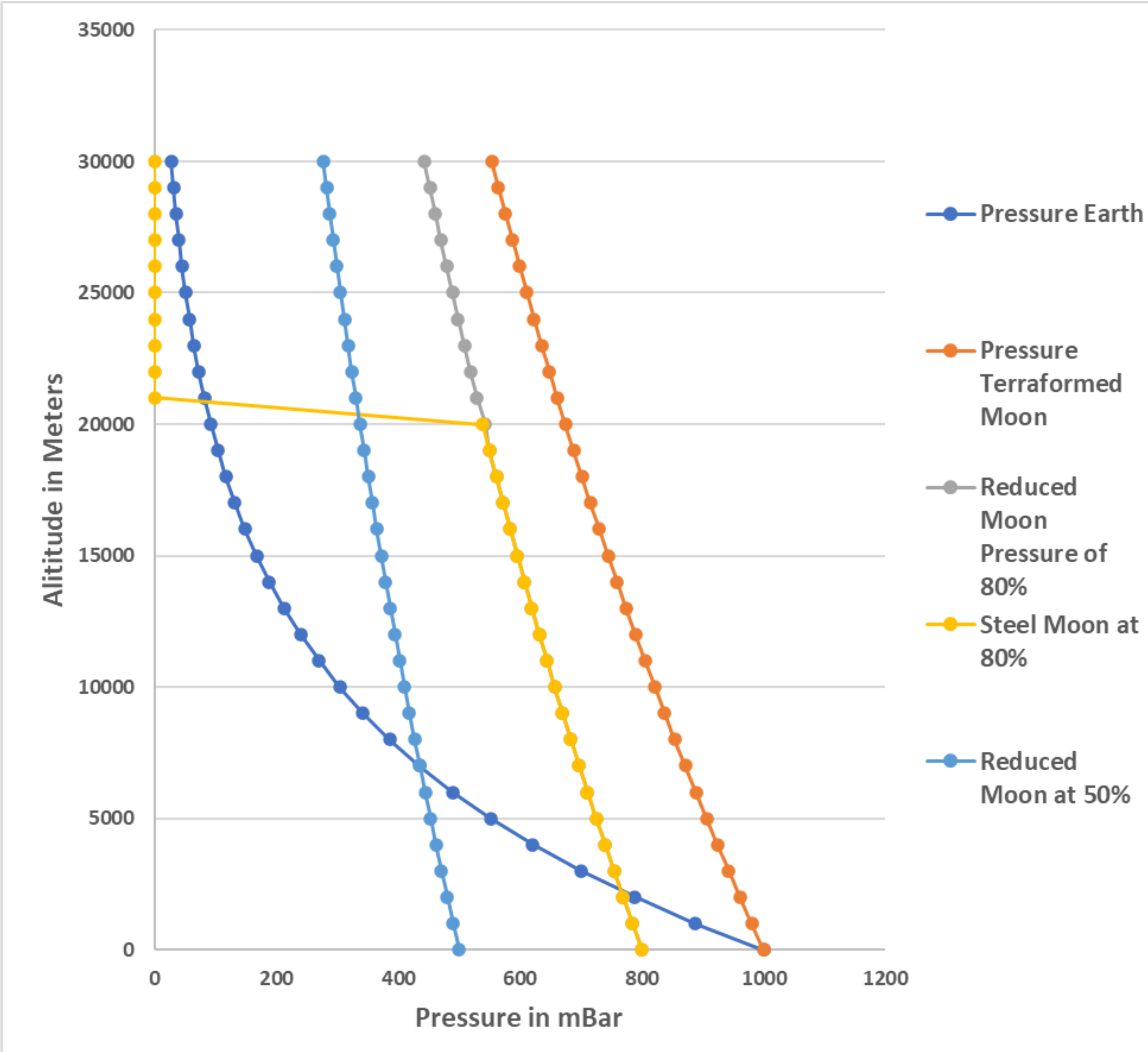


Figure 13-4 Same Chart as 13-3 but showing the effect of a Steel Roof at 20km altitude

Because of the low gravity of the moon, the atmospheric pressure will drop much less quickly than the earth. If we went with a 800mbar surface pressure we would have 540mbar at 20km. On earth this pressure is achieved at about 5150m.

Roof Design and Construction

Roof will be in equilibrium floating on top of the atmosphere. The pressure of the atmosphere is substantial which means that the weight of the 2cm steel roof is far below what the pressure below will require. In addition, the force of gravity further reduces the apparent weight. Table 0-2 shows the equivalent depth of water or lunar regolith to offset the atmospheric pressure. If we locate our roof at 20km altitude where are atmospheric pressure is 540mbar, we could support almost 11meters of lunar regolith with a Specific Gravity of 3.1.

mbar	nt/m2	kg/m2 earth	lunar vertical meters of water	lunar verticle meters SG 3.1
50	5,000	509.68	3.11	1.00
100	10,000	1,019.37	6.22	2.01
150	15,000	1,529.05	9.32	3.01
200	20,000	2,038.74	12.43	4.01
250	25,000	2,548.42	15.54	5.01
300	30,000	3,058.10	18.65	6.02
350	35,000	3,567.79	21.75	7.02
400	40,000	4,077.47	24.86	8.02
450	45,000	4,587.16	27.97	9.02
500	50,000	5,096.84	31.08	10.03
550	55,000	5,606.52	34.19	11.03
600	60,000	6,116.21	37.29	12.03
650	65,000	6,625.89	40.40	13.03
700	70,000	7,135.58	43.51	14.04
750	75,000	7,645.26	46.62	15.04
800	80,000	8,154.94	49.73	16.04
850	85,000	8,664.63	52.83	17.04
900	90,000	9,174.31	55.94	18.05
950	95,000	9,684.00	59.05	19.05
1000	100,000	10,193.68	62.16	20.05

Table 13-2

The steel roof brings up an interesting point- should the roof be free floating or anchored? After some thought an anchored roof is necessary for the following reasons:

- It will permit large elevators to carry people and cargo up and down to the ground.
- It will permit the construction of lunar elevators that extend from the lunar surface, through the steel roof, and into space.
- A free floating roof would be dangerous. The roof will also need to be anchored to the ground in some fashion. If weather currents flow below the roof, they will set the roof in motion. Furthermore, tidal gravitational forces will pull on the roof. The roof does not have the same inertial characteristics as the moon so will move independently of the surface. The roof will need to flex in height to accept minor changes in atmospheric pressure but it would be dangerous if the roof were to start rotating independent of the moon. Some means of anchoring the roof, while permitting some gravitational and weather related flexing will need to be incorporated into the design.

Finally, while a near earth pressure atmosphere may not make sense for the surface of the moon, a hybrid system may be desirable in which a near earth pressure is below the steel roof but above is a much more tenuous atmosphere. A small atmosphere above the roof, say 100 mbar, would have several advantages:

- It will provide an atmosphere suitable for aerobraking but will not lose as much atmosphere as a moon that is at near earth pressure.
- The more tenuous atmosphere would still permit orbiting satellites at high altitudes
- It would provide some cosmic ray protection
- It would reduce the thickness of the steel roof and regolith required
- If the atmosphere were mostly oxygen and nitrogen, it would allow for airbreathing vehicles above the roof for travel

I tend to believe that an atmosphere of 1000mbar or even 800mbar is higher than it needs to be. With the very light lunar gravity, movement will be relatively easy and less strenuous. Winged aircraft would have no problem flying in a moderately thin atmosphere since gravity is so low. In general humans on earth function quite well down to about 800mbar. If the oxygen content of the atmosphere were increased to say 30%, humans should be able to function down to about 600mbar without any ill effects.

Using this as a baseline, I would propose the following:

- Mean surface pressure 600mbar
- Pressure above the steel roof 100mbar

What will be the target temperature be beneath the roof? What will the weather be like?

One of the primary advantages of enclosing the moon is to eliminate the large temperature swings. Without greenhouse gases the average temperature at the earth/moon distance from the sun would be about -15C. On Earth the average temperature is actually around 14C but this masks large variation with altitude and longitude. For this analysis I set the moon temperature to the same as the earth. On the moon we can likely eliminate all or most of the temperature difference between the poles and equator. As on earth, higher elevations will have lower temperatures due to adiabatic cooling but due to the more gradual drop off in pressure, the condensation and cooling effect will be much less drastic. In addition, we may choose to set our temperature at a warmer 18C, usually regarded as optimum to minimize heating and cooling on earth. This will only slightly raise our atmospheric pressure (at 20km we will be at about 543mb vs 540 for 14C).

This temperature would be our target for our mean sea level.

One goal with our design is to ensure that the roof does not drop below 0C as this will cause water to condense and form large ice sheets, that when they break off could drop down and cause injury or damage. Because of the 10+ meter thick insulating regolith covering on our roof temperature extremes would be minimized and we should remain above 0C.

The temperature will have to be able to be regulated in several ways- by varying the amount of sunlight admitted below the roof, by changing the moon's surface albedo, and by active heat transfer and cooling.

How much light is needed and how will it be provided?

A light intensity of 10,000 lux would be suitable for crop growth and for humans. This is only 10% of peak sunlight but should be adequate for crop growth. The roof should provide this amount of light for 12 hours per day over any particular point. Because of the nature of the roof, it may be better to have the entire moon on a single light cycle and illuminate the whole roof for 12 hours. This decision can best be made when the nature and source of the lighting is determined.

The light can be provided artificially, but this seems very problematic. Since the light levels we are shooting towards are only 10% of natural light levels, and solar cells, assuming the technology continues to advance, should be about 30% efficient. Assuming an advanced, high-power versions of LEDs are created that are 50% efficient, we would recover only 15% of the energy falling on the moon to create our artificial light which would require us to cover 2/3rds of the roof surface with solar panels. Furthermore, to manufacture artificial light sources that totally illuminate the moon's 38million km at 10000 lux seems to be excessively challenging.

Alternatively, we could install large glass panels that cover 10% of our roof. The problem with this is that sunlight would be constant for 14 days. To maintain our 12-hour cycle (or whatever other cycle we choose) will require that these transparent panels be able to be closed as needed with shutters or blinds. This only addresses the daylight portion of the moon; we would then have to address the night side. I see several solutions.

- Artificial Lighting

- Light pipes or reflected light that direct sunlight around the steel roof to the night side
- Large mirror at the lunar L2 point about 63000km from the center of the moon. This point is not gravitationally stable, but I could imagine a space elevator tethering it to the ground and positioning the mirror just beyond this point. A reflective surface, if it were to have the same apparent diameter as the sun, would be approximately 600km in diameter.
- A large mirror that rotates around the moon once every 24 hours. As with the L2 point, the earth gravitational field would quickly distort its orbit, but if sufficiently light so that it could maneuver as a solar sail, it could continuously optimize its orbit.

As far as daytime light transmission, the easiest is to have large windows, perhaps 3 meters on a side, that are scattered over 10% of the shell surface. However, since these windows only measure $9m^2$, we would need 4.2 trillion windows to cover the whole shell. I am not sure this is the most efficient way of allowing light onto the surface and I can see two options to reduce this number considerably. The first is to just increase the window size substantially- perhaps to 5m or 10m on a side- but the pressure on a window would be quite large and even a 600mbar difference over a 100m square window is extremely large and may make this size window impractical.

Alternatively, it may be easier to consolidate this requirement into perhaps only about 1/10 the amount of windows by having large mirrors that beam light to a central mirror that projects it through a single aperture. If we used a larger 6m on a side window with an mirrors collecting and directing an energy flux 10x normal sunlight, we could reduce the number of penetrations to 105 billion.

What will the roof structural material be made of and how thick?

The roof will be made of metal. Steel and Aluminum would be the prime candidates.

The advantages of aluminum are its high prevalence and its light weight.

Steel is an alloy of iron that is mixed primarily with Carbon (about .2%). Carbon appears to be rare on the moon which could present a challenge.

Steel is my preferred material for the following reasons:

- Weight is not critical.
- Steel is stronger than aluminum.
- Steel is mostly iron and as such plates can be moved around with electromagnets.
- Steel is very tolerant to varying stress without failing. It is one reason the leaf springs are made of steel as opposed to aluminum.

The roof can be made exclusively of plates of steel welded together. This would be the simplest to construct.

However, we may choose a slightly more complicated structure of plates with girders. The advantage to this design would be:

- Greater resistance to large tears in the event of a puncture.
- Girders can carry our power cables/utilities.
- Girders form a convenient attachment point for our anchors.

Besides the intrinsic strength of steel the moon will have many meters of regolith covering which will mitigate and dissipate meteor impact energy. Meteors impacts will have the following characteristics:

Target is for each square kilometer of roof, mass of roof will equate to 99.5 percent of force on roof, with .5% provided by tension cables.

For each square meter the pressurized atmosphere would exert a force of 54,000nt or 54kn. Over 1 square kilometer, or 1,000,000 m^2, the total force will be $5.4x10^{10}$ nt or 5.4 billion nt. The tension cables, if they were to provide 1% of the downward force would need to provide 540,000kn. A 52mm steel cable has a minimal breaking strength of 1420kN with a working load limit of 285kn and has a mass of 10kg/m- but due to the lower gravity, would effectively be only 1.67kg/m. If our cable were 28km long (the maximum we can expect) the load on the top of the cable, under the moons 1/6 g, would be 46.4kn. We would have to add additional load, either by attaching mass to the cable or by applying tension at the bottom of the steel rope. Using a working limit of 250kn we would need 2160 cables per square kilometer.

With a mass of 10kg per meter but to convert to lunar gravity only 1.67kg/meter. Using our maximum cable length of 28km our cable will exert a force of about $4.58x10^5$ nt, or , or 458.7kN.

Roof will consist of steel plate 20mm thick. On Earth this equates to 156.8kg mass but on the moon this will weigh the equivalent of only 26kg.

Anchor cables

Raw materials

Rope Diameter		Minimum Breaking Strength		Working Load Limit		Weight	
(in)	(mm)	(lb_f)	(kN)	(lb_f)	(kN)	(lb_m/ft)	(kg/m)
1/4	6.4	5480	24.4	1100	4.89	0.11	0.16
5/16	8.0	8520	37.9	1700	7.56	0.16	0.24
3/8	9.5	12200	54.3	2440	10.90	0.24	0.36
7/16	11.5	16540	73.6	3310	14.70	0.32	0.48
1/2	13.0	21400	95.2	4280	19.00	0.42	0.63
9/16	14.5	27000	120.0	5400	24.00	0.53	0.79
5/8	16.0	33400	149.0	6680	29.70	0.66	0.98
3/4	19.0	47600	212.0	9520	42.30	0.95	1.41
7/8	22.0	64400	286.0	12900	57.40	1.29	1.92
1	26.0	83600	372.0	16700	74.30	1.68	2.50
1 1/8	29.0	105200	468.0	21000	93.40	2.13	3.17
1 1/4	32.0	129200	575.0	25800	115.00	2.63	3.91
1 3/8	35.0	155400	691.0	31100	138.00	3.18	4.73
1 1/2	38.0	184000	818.0	36800	164.00	3.78	5.63
1 5/8	42.0	214000	852.0	42800	190.00	4.44	6.61
1 3/4	45.0	248000	1100.0	49600	221.00	5.15	7.66
1 7/8	48.0	282000	1250.0	56400	251.00	5.91	8.80
2	52.0	320000	1420.0	64000	285.00	6.72	10.00

Table 13-3

Steel plate

Steel cables

An 11 meter fill will protect against any asteroid below a few kg.

Nitrogen will almost exclusively have to be imported from comets with either frozen nitrogen or ammonia.

Oxygen can be locally fabricated from separating it from lunar regolith.

Force of atmosphere	54,000 nt	
Steel plate (Earth 156.8kg)	-260nt	2cm steel 260nt
Aggregate fill	-54500nt	At a SG of 3.1 converts to 11 meters
Steel Cable	-240nt	

Table 13-4

Water will be supplied by both local, lunar sources and comets. Comets will likely be the majority, but it is believed that the moon has some water, both at the poles as well as subsurface.

540mbar is a high pressure. To offset this

The steel roof will be primarily manufactured from lunar iron. Steel is typically about 98.5% iron with most of the rest carbon.

Let us assume a roof 20km above the mean radius of 1737.4. The surface area for a 1757.4 km diameter sphere is $3.88x10^{13}m^2$ or $38,810,667km^2$. Steel that is 2cm thick will mass about $1.568x10^8$mt per kilometer and the volume of steel required will be about $776,213km^2$ or $7.76x10^{11}m^2$. The total mass of the steel roof will be $6.08541x10^{12}$mt. Depending on the alloy Steel has a specific gravity of about $7.715kg/m^3$. Iron has a density of 7.874g. This volume of steel is equivalent to a ball of steel 11.4 km in diameter.

Globally, civilization produces about 2 billion metric ($2x10^9$)mt per year. The steel required for our roof is 3 million years of production! This may make the Steel Roof seem impractical. However the intent would not be to build the roof in a year or even a decade. The earths economies do not produce more steel because it is not needed, and it would be a waste of material and energy resources. In 1967 the world only produced 497.2 million mt. If steel production continues to triple every 50 years, in 400 years global production would be 59,049x greater than current and the moon would only need a bit more than 50 years worth of steel. [Steel Production by Country - 1967/2021 - (statisticsanddata.org)](statisticsanddata.org) . Large, mostly automated steel factories in space can be built that can produce even more. Pollution would not be a problem. Furthermore, if the initial roof were built that was only 1cm thick, the steel required would be half.

Puncture and Disaster Management

One risk of all large structures on the moon is the risk of meteor impact. An extensively terraformed atmosphere would offer considerable protection due to the atmospheric thickness. However a moon with a steel roof would not have an atmosphere. Any impact to the steel roof could cause a puncture which will allow the air out and, depending on the size of the puncture, slowly lower the roof as the air pressure below reduced. However as seen, the roof, in order to remain in equilibrium with the atmosphere below, will have a substantial regolith covering. Any small meteors will be halted by the 10-11m thick regolith covering before puncturing through the steel roof.

Meteorites can impinge on the moon at substantial velocities- anywhere from 25kps to 75kps. We can do some rough calculations on what the effects of a meteorite are on our regolith.

Size (kg)	Volume (m3)	Diameter	Energy (MJ)	TNT	Crater Diameter (meters)	Crater Diameter	Depth	Frequency (1 sq km)	Frequency Moon	Comments
0.01	0.000	0.019	13	3	2.04	0.78	0.20	0.0100	379,322.96	**2 cm regolith, 2 cm steel**
0.10	0.000	0.041	125	30	3.87	1.57	0.39	0.0010	37,932.30	**1 m regolith, 2 cm steel**
1.00	0.000	0.089	1,250	299	7.40	3.15	0.79	0.0001	3,793.23	**1.5 m regolith, 2 cm steel**
10	0.004	0.192	12,500	2,988	14.10	6.29	1.57	0.0000	379.32	**3m regolith, 2cm steel**
100	0.037	0.414	125,000	29,876	26.70	12.56	3.14	0.0000	37.93	**6m regolith, 2cm steel**
1,000	0.370	0.891	1,250,000	298,757	50.60	25.03	6.26	0.0000	3.79	**12m regolith, 2cm steel, Marginal protection**
10,000	3.704	1.920	12,500,000	2,987,572	96.10	49.94	12.49	0.0000	0.38	**Insufficient protection**
100,000	37.037	4.136	125,000,000	29,875,717		124.55	31.14	0.0000	0.04	**Insufficient protection**

Table 13-5 Calculated force based on meteorite traveling at 50kps

What these calculations show is that a roof with 6m of regolith is sufficient to protect from meteorites of up to 100kg, and may offer protection to meteorites up too 1000kg. For larger meteorites, an active defense will be needed, but larger meteorites are extremely rare- occurring on the order of .38 times somewhere on the moon every year.

Materials

The steel moon will require steel of with an average of 2cm for our roof. The new diameter of the moon will be 1757.4km. The approximate enclosed volume of atmosphere will be 767,400,000km3. With our roof, the moon will now appear about 1.15% greater in diameter, but about 2.3% larger in area. As seen from earth, eclipse events will be slightly longer with a wider path of totality.

For planning purposes we will assume a target atmospheric pressure on the lunar surface of 800mb. If the moon did not have a roof the mass of the atmosphere can be calculated as:

P= 800mbar=80,000nt/m

a= 3.793×10^{7} km= 3.793×10^{13}m

F= 80,000x3.793×10^{13}= 3.0344×10^{18}

m= F/a= $3.0344\times10^{18}/1.622$

Total Mass= 1.871×10^{18} kg

With a floating roof we can reduce this. Our new mass will simply be the mass with no roof subtracting the mass of the atmosphere above our roof.

P= 540mbar=54,000nt/m

F=54000x3.793×10^{13}=2.0478×10^{18}

M= $1.912\times10^{18}/1.622=1.179\times10^{18}$kg

New mass

$M_{\text{atmosphere with roof}} = m_{\text{no roof}} - m_{\text{atmosphere above 550mbar}} = 1.871 \times 10^{18} - 1.179 \times 10^{18}$

$\text{Mass}_{\text{atmosphere with roof}} = 6.924 \times 10^{17}$

Our atmospheric mass is now only about 30% of that required for a roofless moon.

Components in dry air		Volume ratio = Molar ratio compared to dry air		Molar mass	Molar mass in air		Atmospheric boiling point		
Name	Formula	[mol/mol$_{air}$]	[vol%]	[g/mol], [kg/kmol]	[g/mol$_{air}$], [kg/kmol$_{air}$]	[wt%]	[K]	[°C]	[°F]
Nitrogen	N_2	0.78084	78.084	28.013	21.872266	75.511	77.4	-195.8	-320.4
Oxygen	O_2	0.20946	20.946	31.999	6.701942	23.14	90.2	-183.0	-297.3
Argon	Ar	0.00934	0.934	39.948	0.373025	1.29	87.3	-185.8	-302.5
Carbon dioxide[1)]	CO_2	0.000412	0.0412	44.010	0.018132	0.063	194.7	-78.5	-109.2
Neon	Ne	0.00001818	0.001818	20.180	0.000367	0.0013	27.2	-246.0	-410.7
Helium	He	0.00000524	0.000524	4.003	0.000021	0.00007	4.2	-269.0	-452.1
Methane	CH_4	0.00000179	0.000179	16.042	0.000029	0.00010	111.7	-161.5	-258.7
Krypton	Kr	0.0000010	0.0001	83.798	0.000084	0.00029	119.8	-153.4	-244.0
Hydrogen	H_2	0.0000005	0.00005	2.016	0.000001	0.000003	20.3	-252.9	-423.1
Xenon	Xe	0.00000009	0.000009	131.293	0.000012	0.00004	165.1	-108.1	-162.5
Average molar mass of air					28.9647				

1) According NASA CO_2 level in 1960 aprox. 320 ppm, 1970 aprox. 328 ppm, 1980 aprox. 341 ppm, 1990 aprox. 356 ppm, 2000 aprox. 372 ppm, 2010 aprox. 390 ppm and 2020 aprox. 412 ppm

Table 13-6

In the below referenced quantities the following assumptions are made:

- Regolith mass is calculated based on exactly counteracting atmospheric pressure.
    - The regolith depth for the 800mbar "reference" atmosphere is assumed to be 10.6m – equivalent to 530mbar. Using the lunar roof diameter to calculate surface area, this equates to 38,810,634 km2. If covered to a depth of 10.6m this works out to 411,393km^2.
    - For the 500mbar atmosphere the depth is 3.97m.
- Water assumes the moon has a layer of water 100m deep spread across its entire surface. The earth has about 1.4billion kilometers^3. This works out to a layer of water if evenly distributed across the earths 5.1×10^8 million km^2, with a depth of 2.7kilometers. For the moon with a surface area of 3.793×10^7 square kilometers, it would work out to a volume of 379,300km^2 .
- Depending on the selected atmospheric pressure the atmospheric contents will be adjusted. The earths atmospheric mass is approximately 5.1×10^{18}kg or 5.1×10^{15}mt. For planning purposes:
    - For an 800mbar atmosphere is assumed to be primarily Oxygen (24%) and Nitrogen (75%). In addition, because of its criticality toward life, CO2 will also be required with a average content of .04%. In addition, water will also exist but this will come from our normal water supplies and will average about 1%. All other components are minor and assumed to be introduced via meteorite impact. The goal will be to keep them below 1%.
    - For a 500mbar atmosphere the content will be Oxygen 41% and Nitrogen 58%.

To construct the Steel Moon we will need the following materials:

Material	No Roof 800mbar	Pct	No Roof 500mbar	Pct	Steel Roof 800mbar	Pct	Steel Roof 500mbar	Pct	Source
Steel (2 cm)	0	0.00%	0	0.00%	6.016E+15	0.136%	6.016E+15	0.144%	
Iron	0	0.00%	0	0.00%	5.925E+15	0.134%	5.925E+15	0.142%	Lunar
Carbon	0	0.00%	0	0.00%	9.023E+13	0.002%	9.023E+13	0.002%	Asteroid/Comet
Atmosphere	1.871E+18	33.03%	1.169E+18	23.56%	6.080E+17	13.796%	3.812E+17	9.119%	
Nitrogen	1.331E+18	23.50%	6.381E+17	12.86%	4.326E+17	9.816%	2.080E+17	4.976%	Comet/Kuiper Belt
Oxygen	5.135E+17	9.07%	5.151E+17	10.38%	1.669E+17	3.787%	1.679E+17	4.017%	Lunar
CO2	1.271E+15	0.02%	1.037E+15	0.02%	4.132E+14	0.009%	3.380E+14	0.008%	Asteroid/Comet/Kuiper Belt
Miscellaneous	2.501E+16	0.44%	1.514E+16	0.30%	8.128E+15	0.184%	4.934E+15	0.118%	
Water	3.793E+18	66.97%	3.793E+18	76.44%	3.793E+18	86.067%	3.793E+18	90.738%	Comet/Kuiper Belt
Total	**5.664E+18**	**0.00%**	**4.963E+18**	**100.00%**	**4.407E+18**	**100.000%**	**4.180E+18**	**100.000%**	

Table 13-7

All materials required will be on very large scales. Water will make up the biggest percentage followed by Regolith. However, the regolith will be locally sourced and abundant. Oxygen, while not available as O2, is the most prevalent element and can be processed or separated out of lunar soil (see next section). If we reduce our pressure to 500mbar our required volumes for everything except the water, will be reduced by nearly 50%.

Regolith will be processed for He3 and other volatiles before it is scattered over the roof. Furthermore, during the mining of iron, oxygen will be separated and stored.

Since liquid water is far away the most voluminous material, the nearly $4x10^{15}$ mt would represent a very large mass and would equate to a ball of ice over 190km in diameter.

Nitrogen will be the most difficult item. Most comets, Kuiper belt or Oort Cloud objects will have their largest single component as water. Nitrogen, whether frozen or as part of ammonia, will likely be a fairly minor component.

If we were to look at sheer volume of material, assuming standard densities:

What the table shows is that after the regolith a majority of our raw materials will need to come from Comet or Kuiper or object. Certain types of asteroids are a good source of iron and other metals, and certain asteroids may be sources for carbon and perhaps water but they are poor in other volatiles. Nitrogen can either be found frozen or as ammonia. The table shows the fact that almost all of the materials needed are Oxygen and Nitrogen and that Nitrogen is the most problematic.

Reducing the mean pressure from 800mbar to 500mbar will reduce your required atmospheric mass by about half. The positive and negative aspects would have to be carefully weighed. A disadvantage is our regolith covering will be about half as thick- providing less protection from meteor strikes. My initial approach would be to design the roof for the 800mbar standard, but only initially bring the pressure up to 500mbar. If the comfort level is sufficient and the colonists are OK with this level, they can choose to leave it at 500mbar.

To get an idea of the volumes required figure 0-6 shows various diameters of a spherical Kuiper Belt object with their mass. The object is assumed to be made up of water and other volatiles as well as a small percentage of materials like iron, nickel, carbon and silicon. The Specific Gravity is assumed to be 1.6. Asteroids usually have a much higher specific gravity of 2 to 4 but comets are usually closer to .6. What the graph shows us is that for a Kuiper Belt object would have to have a diameter of about 178 miles to provide enough materials for an 800mbar terraformed moon with roof. No comets have ever been seen this large. Instead, we would likely be looking at a Kuiper belt or Oort cloud object. Because they are larger than comets, they frequently have higher SG than a comet. Assuming one with a SG of 1.5 we get Figure 0-6.

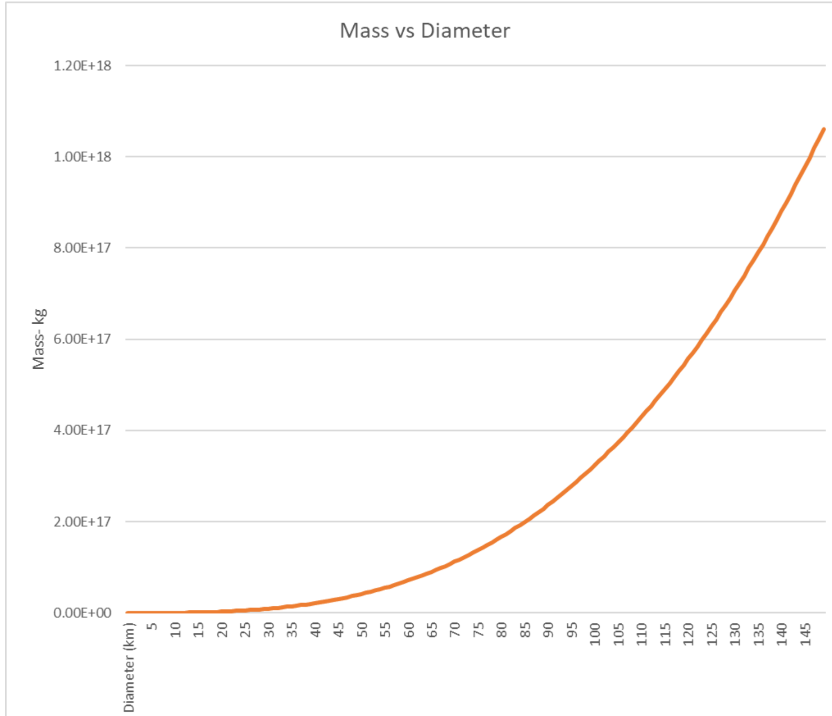


Figure 13-5

Material Source- Lunar Regolith

While the consistency and availability of materials in the lunar regolith is based on only a few samples

Figure 13-6

mostly collected by the Apollo astronauts, the reality is that a large quantity of regolith will need to be moved to cover the lunar shell. It is probably prudent to process this material for needed volatiles and other elements. According to one study if we were to process one square kilometer of regolith we would separate out the following per cubic km:

Let us assume we process 3m deep regolith over the whole surface of the moon. This equates to processing 113,790km. From this we would get:

Volatile	Quantity per cubic km (ton)	Quantity if mined over whole lunar surface (113790km3) to 3m (ton)	ton	Comment
H2	201	22,871,790.00	2.29E+07	
H2O	109	12,403,110.00	1.24E+07	
He	102	11,606,580.00	1.16E+07	
CO	63	7,168,770.00	7.17E+06	
CO2	56	6,372,240.00	6.37E+06	
CH4	53	6,030,870.00	6.03E+06	
N2	16	1,820,640.00	1.82E+06	
3He	33	3,755,070.00	3.76E+06	kg; used for Nuclear Fusion

Table 13-8

Even though these number are substantial, they are almost insignificant compared to the actual volumes needed. The volume of water above represents only 12.4m^3.

The uncertainty of the prevalence of lunar volatiles is illustrated by the conclusion from the SOFIA telescope that in the crater Clavius, each cubic meter of soil has the equivalent of 12oz (340.2 grams of water). Clavius is not near the poles and is exposed to considerable sunlight. This prevalence works out to 340.2 mt/km2 of 3x greater than what was determined to be in the Apollo samples.

Even more importantly, the liberated 201 mt of h2 can be combined with the very prevalent and available oxygen to make about 1800mt of water per cubic kilometer. This created water, when combined with the liberated water will produce 2000mt per kilometer. Our new numbers indicate a much more sizeable 2.18x10^{8}mt available.

While these quantities are low, it should be pointed out that we will not need to go to our target pressure of 800mbar- we will gradually increase our pressure to account for gravity.

Lunar Mining

Mining below the moon, as well as processing of meteorites and lunar regolith, should supply us with all the iron we need. However, it will likely not provide a huge source of volatiles nor the carbon.

Construction

The Steel Roof does not need to be constructed in one shot. Instead, a core will be built of steel plates that ware welded in a concentric spiral. Once the steel roof is of substantial size, perhaps several kilometers in diameter, small atmospheric pressure will be applied- perhaps 50mbar. Some cover regolith will be applied to ensure that the roof plate does not tear. A sequence of adding slight pressure while offsetting the stress with regolith topcover will be established. The plate will be considerably larger than the pressurized bubble and the mass of the plate, combined with a perimeter of regolith cover will prevent the escape of our atmosphere. Large rocks and bolders will have to be managed do that they do not puncture the roof where the roof rests on the ground. Figure 13-7 shows the overall scheme:

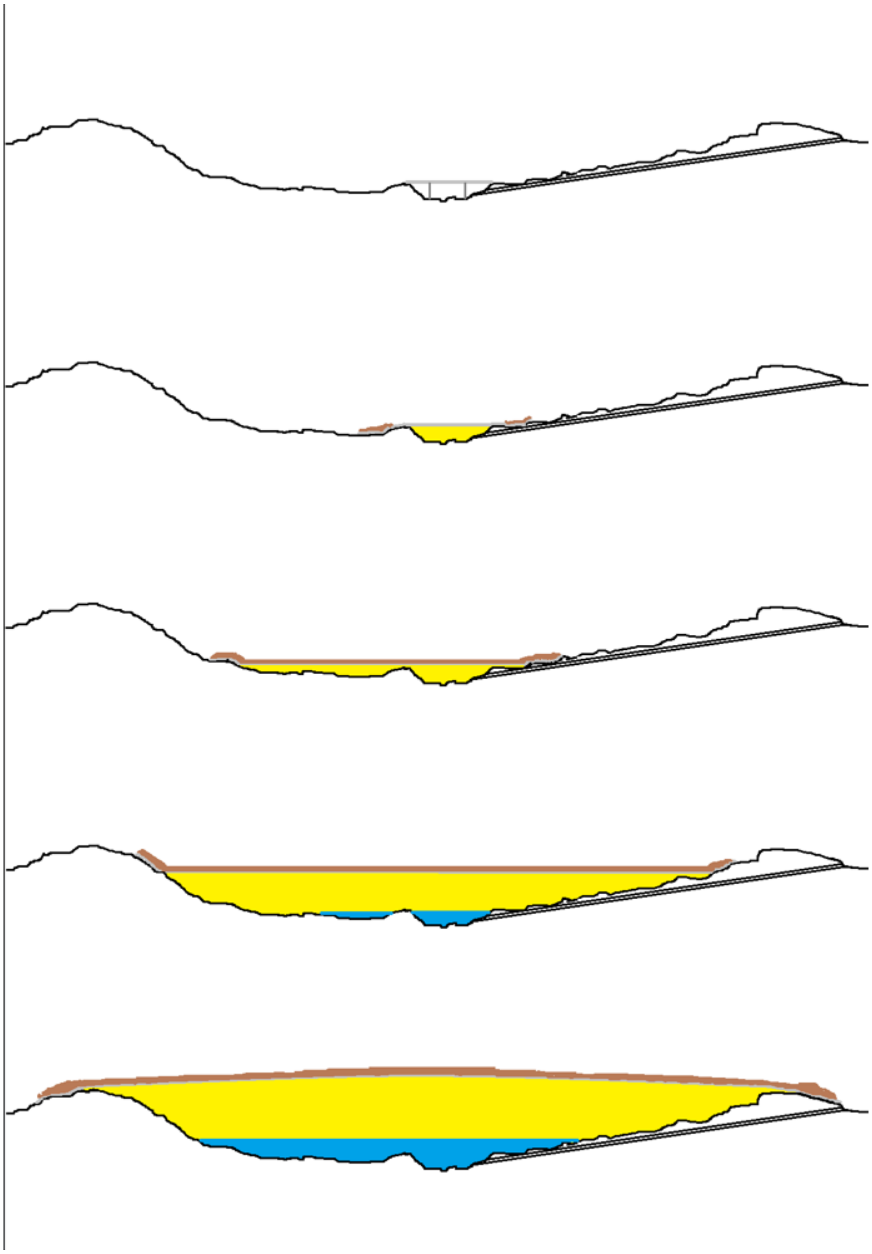


Figure 13-7 Construction of Steel Roof over time. Yellow is atmosphere, Blue is water, Amber is regolith top cover. Not shown- spaced periodically steel cables will extend down from the roof to anchor it but that the cables will have considerable give to permit roof to flex.

Step 1, Construct a section of roof supported off the ground by scaffolding within a crater. Lay pipe or dig a tunnel to outside the rim of the crater.

Step 2, Add a small atmosphere beneath the steel roof to inflate it. On the roof place small amounts of regolith to ensure stress is not exceeded. On top of the roof around the perimeter, some extra material (in amber on drawing) is added to keep the atmosphere from escaping. Pressure would be fairly low- around 50mbar to keep stress levels low. To offset this pressure about 1m of lunar regolith will need to be applied as cover (Table 13-2).

Step 3- Continue to weld steel plate in a spiral or circular pattern while gradually increasing the atmospheric pressure and regolith top cover.

Step 4-Continue to introduce volatiles to the atmosphere while introducing water. As the bubble of the roof expands, move anchoring thicker regolith to the edges to keep atmosphere contained.

Step 5- Repeat. For large uneven surfaces including large boulders, surface will have to be leveled or some scaffolding constructed. At this point roof may be at 500mbar and extend 30km in diameter with the regolith top cover at about 10m. At 500mbar, with about 40% Oxygen should provide a suitable atmosphere (see Figure 4-2). Small towns and cities could be established under the roof. People, animals and plants should be able to function with little discomfort other than low humidity.

Note that with this technique we will be moving many kilometers of regolith to cover the roof. This may be an opportunity to process the regolith to remove iron, needed minerals, oxygen, any volitiles including water and He3 as part of the mining process. We can use the recovered water, oxygen, carbon and volatiles to reduce the amount of materials that need to be imported.

Delivering the Atmosphere and Water

Delivering the vast quantities of material will be extremely challenging so as was outlined in the previous section, the initial work for the first few decades will be restricted to a very small section, perhaps less than 1% of the lunar surface.

To eventually extend this concept to the whole moon will take an industrial capability far beyond what will likely exist for another could of hundred years- but if the work is done gradually it can be done. As such, any suggested approaches will be extremely speculative.

The following are some assumptions that we will make:

- The complete terraforming project will be at least 500 years
- Smaller areas will be terraformed and suitable for planting of initial plants within 20 years. Human rated areas will be available within 50-60 years

The ideal candidate for supplying resources will be a Kuiper belt object on the inner portion of the Kuiper Belt. We will assume an orbital velocity of 4kps. This will place the object at 8.3 billion km from the sun, or almost 50% further than Neptune.

There are two primary means of transporting the raw materials to the moon. We can choose an asteroid but an asteroid will not have all the volatiles, primarily Nitrogen that we would require. A Kuiper belt object would have the Nitrogen but will take decades to get to the moon. I foresee using both- the asteroid to provide the water and carbon, and the Kuiper belt object to provide the water, Nitrogen and Carbon Dioxide.

We can deliver the material in two ways.

Asteroid and Kuiper redirect.

Mass Driver.

We will look at both.

- Diversion of a large Kuiper belt object(s). Since water and Nitrogen are the two materials needed the most, a Kuiper Belt is likely to be better than an asteroid.
    - Assuming a SG of 1.5, and 50% of the mass being wasted we will need Kuiper Belt object about 8.8×10^{18}kg which would have a diameter of around 224km.
- Projecting mass via mass driver to impact the moon
    - Assume the total mass of Kuiper belt object is the same, but only the needed material would be launched. Mass ad Diameter would remain the same.
    - Assuming each packet is 1000kg, we would need to launch 4.414×10^{15}
        - If we launched one packet per minute we would need to launch non-stop for 8.4 billion years.
        - If we launched one packet per second we would need 140million years.

We will look at both options and compare.

Diverting a large Kuiper belt object(s)

Projecting mass Momentum Spinarm or via mass driver

A Momentum Transfer (Spinarm) is likely the simplest and most elegant solution, though a mass driver would also work. Either way, much of the mass of the asteroid or KO will be wasted- perhaps 50%.

For an object that is orbiting at about 4kps, to have a periapsis at about 1 AU (150 million km) a dv of about 3.3 in a retrograde impulse would need to be applied. A large MT would have sufficient capability to send a payload to earth, though the payload may be restricted in mass to a 10000mt. Heavier payloads may be better served by a large mass driver. Either way the payload would be a standardized container consisting of 90% nitrogen ice or water. An aircraft carrier can accelerate a 36000 kg aircraft at about 3.67g. If we reduce the acceleration to 2g, an equivalent mass driver would be able to accelerate a 66,000kg payload. For simplicity, lets assume each cargo transporter will have about 60mt of payload (nitrogen, water etc) and about 6mt of spacecraft structure, power plant and propulsion system.

To deliver the required 4.326x1017 kg of Nitrogen, we would need 7.2 trillion launches. We will have an additional challenge in that at the periapsis, the payload will be screaming at about 42kps. If it were timed and correctly orientated it could intercept the earth and moon when the moon was revolving around the Earth in the same direction as the payload so impact speeds ideally could be as little as 11-12kps. Unfortunately at this speed any cargo would hit the moon with some much energy that almost all the volatiles would escape. Furthermore the cargo would have taken on the order of 160years to drop down from the Kuiper Belt! A source for Nitrogen or water that is closer- Pluto or one of the outer moons, would shorten this, but any cargo traveling on a ballistic trajectory would still hit the moon at close to 12 kps.

There are possible mitigating solutions- if the initial cargo pallets are powered with electric thrusters that would activate the last few years to modify the velocity down to 2-4kps, then most of the impacting payload would not be lost. As the moon built up a modest Mars type atmosphere, small payloads could enter the atmosphere at higher speeds because when they hit the atmosphere they would transer a lot of their energy to the large volume of atmosphere so the extra volatiles would not escape. Unfortunately but to get to even a 5mbar atmosphere would require billions of cargo pallets. To calculate the mass of a 5 mbar atmosphere:

$$m_{col} = \frac{p}{g}$$

With:

$$p = surface\ pressure = 500Pa$$

And

$$g = 1.62\ m/s^2$$

Solving

$$m_{col} = \frac{500}{1.62} = 309\ kg/m^2$$

Mars has a surface area of $3.8x10^{13}$ m^2. Solving for total mass of a 5mbar atmosphere we get $1.2x10^{16}$ kg. With each nominal container hold 60,000kg, we would need 267 billion cargo pallets.

Specifications for the Steel Moon

- 800mbar mean pressure
- 20km roof height above mean
- 2cm thick steel
- 10.6 m thick regolith on top of roof
- Able to withstand meteorite impacts up to 1000kg and about 1m in diameter
- Active meteor defense for larger objects
- Surface daytime lighting will be 1200lux
- Target average lunar surface temperature will be 20C

The two thousand year project

The scope of the project indicates that a long period of time will be required to complete the project. However the steel roof should be usable within the first decade or so, just be restricted in area and pressure.

If we assume a 2000 year project we will have to have a very large steel making project. If spread out over the entire project duration we will need to make $3.0427x10^{12}$mt of steel per year. This is 1500x more steel per year than the world currently produces. This would make enough steel to cover 15,000km per year. In ten years 150,000 km would be covered. At this point you would inject gas into the center. Steel is rather flexible and will bend upwards, creating a space underneath. Only enough atmosphere would be injected to fill the center few kilometers wide and perhaps a hundred meters tall. The initial atmosphere will be very low pressure, enough to raise the roof so likely only about 100 mbar. All the infrastructure can be tested at this point including the lighting.

Construction

The following equipment will be needed:

Mark III Miner- excavate regolith

Chapter 14 - Terraforming Mars

Terraforming is the process of intentionally modifying a planet for a particular purpose- usually in the context of making it more Earthlike and comfortable. I building the Steel Moon and Steel Mars were not challenging enough, the next steps terraforming, are an order of magnitude greater for most planets or Moons.

Mars		Comments
Diameter		
Mass		
Density		
Gravity		
Escape Velocity		
Distance From Primary		
Length of Day		
Average Surface Temperature	213k	
Atmospheric Density	610Pa (6.1mbar)	95% CO2.
Atmospheric Mass	$2.5x10^{16}kg$	

Table 14-1

Mars also has plenty (though uncertain) quantity of water0 estimated at at least 5 million km3, which equates to a worldwide ocean 35m deep. This is a lot less than earth (2700m deep) but is the lowest number for Mars capturing only clearly identified ice. It is believed many times more water exists in liquid aquifiers.

The equivalent of 35m a map of Mars would look like:

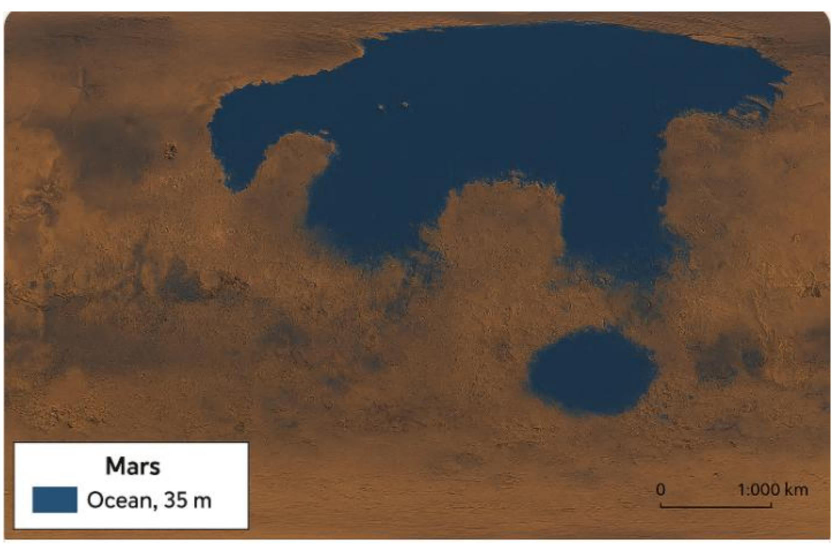
:

Figure 14-1

The (perhaps) Best Planet for Terraforming

Mars is probably the easiest planet to Terraform. However some aspects of terraforming are (relatively) easy but rapidly get extremely difficult.

The biggest issues with Mars is its low gravity and extreme cold. Warming Mars would both release frozen volatiles (primarily CO_2) and allow for liquid water. To make Mars more habitable, Nitrogen would need to be imported and Oxygen would need to be added to the atmosphere (either imported, separated from water via electrolysis, or created via photosynthesis). As opposed to the moon, or most other planets in the solar system, Mars has a day that closely mirrors earth at about 24hours 32 min and its gravity, while little more than a third of earths, is twice that of the moon.

To make the surface habitable as earth would be extremely difficult- but much easier than the moon. Advantages that Mars has over the moon are:

- Approximate 24 hour day
- Twice the Gravity
- Extensive volatiles including water

However we can come up with several intermediate steps to bring it closer to this goal. Robert Zubrin outlined an approach that broadly followed these steps (Zubrin & McKay, Technological Requirements for Terraforming Mars, 1993):

- Large Mirror(s) would be constructed at the Mars L2 point. Mirror would be used to raise the temperature of Mars, in particular at the polar regions
- Evaporation of the frozen CO_2 at the poles would raise the atmospheric pressure
- As the pressure and temperature increased, additional CO_2 would be outgassed from the Martian crust
- The increased atmospheric pressure would permit the existence of some liquid water on the surface- but in general the temperatures would still be too low and the water would instead be frozen
- Introduction of other greenhouse gases including H_2 and Methane
- Nitrogen would be introduced into the atmosphere either through asteroids high in ammonia content or direct Nitrogen importation.

The first three items are relatively easy and would likely get you close to 15mbar pressure and warm the planet up a couple of degrees. After that it becomes very difficult and likely a long term (many centuries) project.

Because of its low gravity Mars can never be made completely earthlike but it can be made much closer by beefing up its atmosphere and raising its temperature. If its temperature were raised by a few degrees and the pressure was increased substantially, water could exist as a liquid on the surface. If the temperature were raised sufficiently large subterranean glaciers would start melting and it is likely little or no water would need to be imported. Water is a very effective greenhouse gas so some additional positive feedback would occur. If plants could exist on the surface, they could start contributing to the atmosphere by adding Oxygen. Finally, large quantities of Nitrogen would need to be imported to make the planet even more earthlike.

We could use a modified version of an Occulus as a large reflector or mirror which if placed in either a large orbit or at a planets L2 point and appropriately focused, can add energy (heat) to Mars for to help raise its temperature.

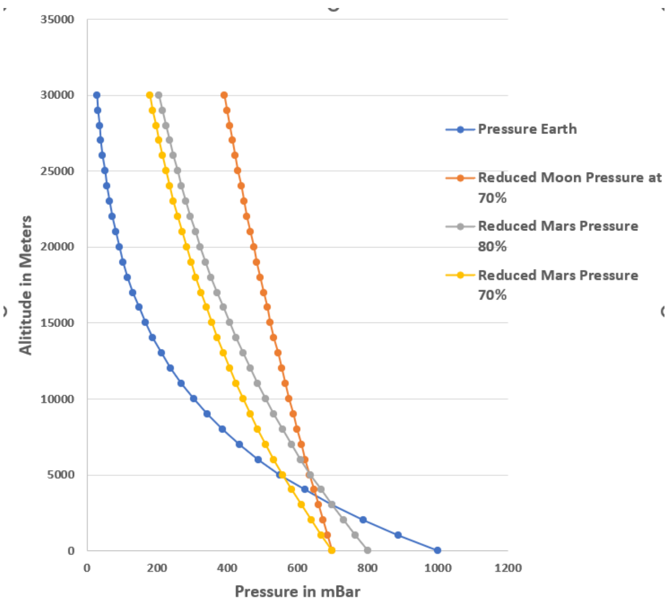


Figure 14-2

Note that one difficulty, as with all terraforming, is that without artificial intervention, these planets will revert back to their normal status at various rates- some taking centuries but others only a few years. Without the added temperatures from a solar mirror, Mars will grow cooler again, its CO2 sublimating out, and its water freezing back onto the surface. Even if the temperature remained elevated, as with the moon, over time any surface water will gradually percolate underground again. One earth, plate tectonics, volcanoes and the high underground temperatures ensure a fair amount of water gets recycled back up to the surface. On Mars and even more so the moon, the geothermal gradient is much lower, meaning that high temperatures are found much deeper in the crust so that it is difficult to get this water recirculated back up to the surface. Few or no volcanoes and no plate tectonics further inhibit water from getting back to the surface. Mars has plenty of water, much of it is just frozen beneath its surface within the top few kilometers. Deep drilling and the introduction of heat will need to be added to permit humans to pump this water back up to the surface to make our terraformed lakes.

Large Solar Mirrors

We need to warm up Mars. As we saw in Figure

X from Chapter 2, sunlight provides less than 600w/m2 at Mars- or less than half that received by the Earth. Beside increasing the mass of Greenhouse gases at Mars, another technology is to build large space mirrors and reflect some of the sunlight back to Mars, in particular the polar caps. The permanent polar caps on Mars consist of small permanent masses of water ice, but every season the polar caps increase or decrease drastically because of Carbon Dioxide which will condenses out of the atmosphere during the extremely cold Martian winters. Because of these large CO2 movements the atmospheric pressure swings seasonally. Nevertheless during the northern summer, while the CO2 cap is rapidly shrinking and tons of CO2 are being released into the atmosphere, the Southern cap is starting to grow, eventually removing all the CO2 that had been released. Large mirrors, pointed at the Polar Caps, can provide enough energy to keep both caps frost free, thereby increasing the atmospheric pressure.

While no large space-based mirrors suitable for providing large quantities of reflected light have been built, the concept has been explored many times. Currently a company called Reflect Orbital is looking at a unique system of building thousands of small reflective satellites to provide light on demand (Refelect, 2025). Both the USSF and private capital have provided money. One of the primary uses would be to provide sunlight to Earth solar farms for periods before sunrise and after sunset. The satellites would be mass produced and orbit at several hundred kilometers above the Earth, and hundreds if not thousands of satellites would be steered toward the target area. The initial versions are planned to be about 324m^2, though future versions could be larger (Mallama, 2026). The mirror would be mylar.

The initial goal is to heat Mars, primarily the North and South poles, enough to keep the CO2 from seasonally freezing out and to release the CO2 that is currently there. This may get the pressure of Mars up to about 12mbar (Jakosky & Edwards, 2018). Some additional CO2 could be released from absorbed gas if the temperature were raised sufficiently as well as the processing of carbonate bearing mineral deposits, but it is unlikely that much more than 15mbar. This would be accompanied by a very small increase in temperature due to greenhouse effect… but likely on the order of only a few degrees.

By building a very large mirror we can both get a much warmer planet, and even higher atmospheric pressure as subsurface CO2 is released and Water vapor begins to get released. Let's assume we position a Mirror at L2 with the goal of it reflecting 325W/m2 (about ¼ the levels at Earth) across the martian far side cross section. Mars solar flux when calculated over the whole sphere is about 111 W/m2 using an albedo of .25.

To calculate the additional heat being added to Mars we would calculate the cross-sectional area of a Mars sized disk, or about $3.61x10^{13}m^2$. At a target of 325W/m^2 the total amount of extra energy added to Mars would be $1.17x10^{16}W$.

To calculate how large the mirror would be we will assume that the mirror has about 85% reflectivity, and the total reflected light illuminates the total Mars disc, probably unrealistically. The solar radiation at Mars is about 590W/m2. At 85% reflectivity this works out to about 502W/m2. To reflect the required $1.17x10^{16}W$ at 502W/m2 we would require an area of $2.33x10^{13}m^2$or a mirror that is 5400km in diameter.

Mars current solar flux is 590W/m2. To calculate the average solar flux absorbed we need to take into the account the albedo and a Geometric Factor. The geometric factor takes into account that Mars is a sphere but intercepts radiation over a disk ($\pi r R^2$) but radiates over its full surface area ($4\pi R^2$). To calculate the current flux where Albedo ≈.25 we would:

$$F_{now} = \frac{S(1-A)}{4} = \frac{589(1-.75)}{4} = 111W/m^2$$

Using our mirror incident radiation at 325W/m2 and using the same formula we would see that our mirror will provide 61 W/m2 of additional energy.

Our new global average now adds up to 172W/m2. With the new total energy we can easily calculate an approximate new temperature using Stephan- Boltzmann equation and taking the ratio of the new vs old energy flux:

$$\frac{F_{new}}{F_{now}} = \frac{\sigma T^4_{eff,new}}{\sigma T^4_{eff,now}} = (\frac{T_{eff,new}}{T_{eff,now}})^4$$

$$\frac{T_{eff,new}}{T_{eff,now}} = (\frac{F_{new}}{F_{now}})^{1/4} = (\frac{172}{111})^{1/4} = 1.55^{\cdot 1/4} = 1.12$$

With $T_{old} = 210K$ our $T_{new} = 1.12x210 = 235K$

Note that 210K is the calculated average using Stephan Boltzmann with an albedo of .25. The reality is because of slightly different albedo and some greenhouse effects, Mars temperature is about 218k, so using this to calculate our 12% increase in temperature we now are at about 244K, or an increase along the lines of 25-30K.

If this new temperature allows for the additional outgassing of CO2 and water vapor, we may add 5-10K more for a final average temperature of 250-255k. This would permit liquid water on certain parts of the planet (around the equator), though the boiling point would be very low- about 28C. Mars also has a surface rich in clays and impermeable ground so will be able to support lakes and oceans if the temperature were raised sufficiently to melt the ice.

In short, the big first step is constructing a large reflective mirror with the following specifications:

	Position	Size (diameter)	Comments
L2 (Reflecting Mirror)	1million km outside Mars	≈5400km	Assume 85% reflectivity; goal 350W/m2 light to Mars

Table 14-2

Unfortunately, while a 30mbar atmosphere looks eminently feasible with this large mirror, most of the limited literature implies plants will need 100mbar or higher to be able to grow. The 30mbar atmosphere will allow some small scale free liquid water but will not be sufficient to make Mars very earthlike. It is possible that the elevated temperatures can liberate more gas but only in the most optimistic scenarios will Mars be able to reach 100mbar. Ideally large quantities of Nitrogen, along with Oxygen would need to be imported over time to supplement the Martian atmosphere. Oxygen, along with hydrogen, can be liberated via electrolysis, but the scale of the operations to meaningfully increase the Oxygen levels, as well as atmospheric pressure, are very long. If the worlds entire electricity supply were transferred to Mars and dedicated to electrolysis, then Mars would reach an atmosphere oxygen pressure of 100mbar after about 30,000 years.

Summary and Conclusions

Mars, while very challenging, can be modified to double or triple its pressure and raise its temperature by 30-35k. After that it gets really hard. Mars' 24hour day/night cycle is a tremendous advantage over the moon, and a large mirror can raise its temperature, however it does not have enough volatiles locked up to become earthlike without the importation of large quantities of Nitrogen and possibly water and oxygen. Electrolysis can add oxygen to the atmosphere but the amount of power is extremely high and with any reasonable expenditure of energy, will take tens of thousands or millions of years.

For a reasonable terraforming approach, the first step required is to increase the heat flux to the planet. A very large reflecting mirror at around the L2 point can add considerable energy which will liberate more of the atmosphere. How much atmosphere can be liberated is still subject to a wide range but it looks like a mirror large enough to vaporize known current CO2 reservoirs will at least double the pressure and more generally elevated temperatures across the planet will liberate large amounts of additional volatiles currently in the soil and underground. A pressure of 30mbar and perhaps as much as 100mbar might be possible, though the upper limit is optimistic. The large mirror outlined would raise the average temperature on Mars from around 218k to about 244k, and a 30mbar atmosphere would further increase the greenhouse effect to a total temperature of 250-255k. Beyond this any additional atmospheric release and increased pressure and greenhouse temperature increases are more speculative. Regardless target pressure of about 200mbar would permit plant growth in sheltered and watered areas. This will require the importation of large quantities of Nitrogen, as well as hydrogen.

Chapter 15 - Terraforming Mercury and Venus

It would seem very difficult to Terraform Mercury and Venus due to their extremely hostile conditions. Nevertheless larger versions of the Solar Occulus could make terraforming possible, and except for Mars, easier than other planets in the solar system.

Terraforming Mercury

Mercury will always be a challenge to reach- it is deep in the sun's gravity well and subject to intense radiation and solar wind. Nevertheless, the planet could be made habitable with some difficulty. Mercury has some tremendous advantages to some of the other planets:

- Relatively rich in metals- iron and nickel in particular. It could be a likely to be a source for building materials
- Close to the sun- any colony will be able to take advantage of solar power in vast quantities
- Being close to the sun, it is possible that large solar power stations will be built- some with large reflective mirrors or large lasers, that will be able to beam power deep into space for solar sails, or even power (see Chapter 7). These stations, possibly built in L2, L3 or L4/L5 would likely be maintained by personnel stationed on Mercury.

Mercury has similarities as well as some advantages and disadvantages over terraforming of the moon. The primary issue with Mercury, as opposed to the moon, is its high solar heat and associated solar cosmic radiation. However, Mercury has a surface gravity almost twice that of the moon (almost identical to Mars) so it would be able to hold onto an atmosphere easier. Unfortunately, Mercury also takes 176 days for one solar revolution so a system of Solar Shades or Occulator, along with Solar Mirrors would be needed to be created to provide a more normal day/night cycle.

The approximate scope to Terraform Mercury are:

- Building a large occulus to lower the temperature
- Building a system of an occulus shade and reflective mirror to provide day and night cycle
- Importing Nitrogen and Water
- Releasing Oxygen from the surface materials

Mercury Occulus

The first order of business in Terraforming Mercury is to build a Solar Occulator to reduce the solar radiation. As with the earth's Solar Occulus, the one around Mercury would be placed at its L1 point. For Mercury, this is a relatively close 220,599 km. Because Mercury is rather small and the Occulus is close to the planet, a fully blocking shade would only be about 11000km in diameter- large for sure but only 9x larger than the 3960km 2% occulator that was being considered for the earth- and far smaller than the one needed for Venus (see next section). If Mercury were fully occulated it would rapidly cool since it is without an atmosphere. Furthermore, a thick heavy occulator could serve to reduce some of the solar cosmic radiation and, if a portion were dedicated to solar power, could provide vast quantities of energy down to the colony via microwaves.

Being a small planet, but having a relatively high gravitational field, the actual mass of an atmosphere would be smaller than an equivalent atmosphere at Mars or, because of the low lunar gravity, far less than the moon without a steel roof. Mercury would need about half the atmosphere mass for an equivalent atmospheric pressure as Mars. A Mercury Steel roof would eliminate the need for an occulator, but as with the Lunar roof, the construction of a steel roof introduces its own challenges and would be a much larger engineering project than an occulator.

As with the moon, Mercury has a major problem. Mercury's daylight is 88 earth days long. During the daylight, our Occulus shield will need to provide alternating daylight on a 24 hour cycle. However, during the night no sunlight will available. I can see several options to address this. We could consider just living with this as with the moon, but the duration of the day is even worse on Mercury and winter would come to Mercury every 88 days. This is not acceptable.

As opposed to Mars where we placed just a single large mirror at L2, with Mercury we would need to build an occulator at L1 to block out excessive radiation and a Mirror at L2 to provide light .

Because of the semi-permanent nature of a Mercury Occulator (it is wise to construct it for several thousand years of maintenance free service), a massive and durable structure would be built. Raw material for the majority of the structure will come from Mercury. Ideally, we would block out about 85% of the solar radiation during the day- and would want to be able to increase this blockage to 100% every 12 hours in order to provide night. In reality, depending on the amount of light and heat that the reflecting mirror provides at night, which is likely to be less than our target of 1400W/m2, we may want to offset our light and heat shortage at night by increasing the radiation at allowed through during the day- perhaps allowing as much as 20% of the light to pass through.

There are several methods that could be used to give us our day/night cycle on the "day" side. We could have two parallel oculi counterrotating with each other that would have several large windows (see Figure XXX) that during "daylight" could admit 15%-20% of the light through to Mercury for 12 hours, and would then fully block all light for the next 12 hours. Alternatively, a single oculus could be built that has several large windows/panels or a central iris that would that would fold open or close to allow sunlight past.

In general, the large eccentricity of Mercury, combined with the gravitational effects of other planets means that the large structures will drift out of the L1 and L2 positions rather rapidly. For this reason we will need constant adjustments to check their drift.

The structure could be made up of regolith, held in place by a fine metal mesh, or instead it may be a single round sheet of steel or aluminum. This would be a robust structure, but will both be so massive that it will be difficult to construct and difficult to maintain positioning since the solar radiation would not be strong enough to keep the structures in position. Alternatively, and a totally different concept would be to have thousand or even millions of smaller structures that would act in concert to reduce the solar radiation- a swarm of osculators.

Perhaps the simplest design is some sort of occulating disk as we discussed for the earth. However, due to its more permanent nature I believe this would need to be much heavier and more massive than the Earth Occulus which may be needed for only decades or perhaps a century. For planning purposes, if we used 5mm steel plate we would have a mass of about 40kg per m2.

The second structure would be to place a large mirror or reflective mirror at the Mercury L2 point. This will lie around 250,000km past the orbit of Mercury. As with the occulator, this will be so far past the planet that it could still be in the L2 point and not be totally blocked by Mercury.

	Position	Size (diameter)	Comments
L1 (Shade)	220,400 km inside Mercury	≈11000km	100% Shade with Panels or Iris
L2 (Reflecting Mirror)	221,000 km outside Mercury	≈3000km	Assume 90% reflectivity; goal 650W/m2 light to Mercury

Table 15-1

As with building the Earth Occulus, I can see the needed supplies being launched via Mass Driver or MT from Mercury.

Assuming that the weight per m2 of surface area is

Importing Nitrogen and Water

Mercury has essentially no atmosphere. If we targeted a surface pressure of 800mbar Mercury's atmosphere would be about $1.6x10^{18}kg$ of about 30% of the Mass of the Earths' atmosphere.

There is essentially no Nitrogen on Mercury so all will have to be imported. If we were to target a 75/25 Nitrogen and Oxygen mix, we would need to import about $1.2x10^{18}kg$ of Nitrogen.

There are vast reservoirs of Nitrogen in the Solar System, including Venus, Earth, Titan and Pluto. Venus is far and away the closest and has over 3X more Nitrogen than the Earth (see next section), however it may be actually easier (though also longer) to drop Nitrogen from Titan into the inner solar system. From Venus' surface, we need about 12kps dv and about 3 months of travel time. The payload will arrive at Mercury and impact at about 7kps. From Titan, optimally positioned in its orbit around Saturn, only about 7.5kps is needed, but the impact speeds will be very high (on the order of 18-19kps) and take several years. These velocities are so high that almost all the nitrogen would flash and boil away as Mercury's escape velocity is only about 4.3 kps. In the case of incoming velocities would likely lead to well over 90% loss, and perhaps half that if inbound from Venus.

We can work around this by more complicated orbital trajectories that use multiple planetary passes around Venus or Mercury to reduce the dv. Once a modest atmosphere is developed, we can use this to slow down incoming payloads to reduce the impact speeds further.

Like Nitrogen, large quantities of water would need to be imported. To have enough water to average a 100m thick ocean we would need $7.5x10^{18}kg$- or almost 7x more massive than the imported Nitrogen. This would be a ball of ice about 248km in diameter.

Unfortunately, Mercury's crust is highly porous, and almost all this water would sink quickly below the surface- over a space of a few years or decades. Further exploration of Mercury would need to be conducted to determine how much water would sink until it was stopped by a compacted barrier or a thermal barrier beneath the surface. It is not unreasonable to assume about 10x more water would actually be required so that until this point was reached, a ball of ice 248km in diameter would need to be imported to Mercury every few years.

Oxygen could either be imported or, with the application of a lot of energy, liberated from the rock.

Carbon, required for life, would also need to be imported. However the surface and atmospheric content on earth totals only about 43,500 billion tons (Phys Org, 2019). Adjusted for the fact that Mercury is only about 15% the surface area of Earth, but its atmosphere is about 30% as massive, I will split the difference and say the Mercury will need about 22.5% of the earth's surface inventory or about 9800 billion tons of carbon. In short:

	Mass	Equivalent Sphere	Notes
Water	$3.75x10^{19}kg$ (Or $7.5x10^{18}x5\ parcels$)	428km (or 5 spheres 248km diameter each)	Assume for planning purposes 5x more water is needed to have a 100m ocean to offset draining into the crust (sourced from Outer Moons, Asteroids, Comets)
Nitrogen	$1.2x10^{18}kg$	130km	Shipped at 55-60K as a solid. Sourced from Venus/Titan
Oxygen	$4x10^{17}kg$	80km	Created locally or shipped at 45-50k as solid
Carbon	$9.8x10^{15}kg$	20km	Sourced from Venus

Table 15-2

As with the Steel Moon and Mars, the amount of mass that needs to be shipped is astronomical. Even large scale operations will take many millennium (and probably far longer) to complete. Just for the water, if about 400mt of water to Mercury every day, it will take almost 250million years to ship the required water. In theory, a 1.1 GWe power plant can ship about 400mt per hour (see Chapter 11). The problem is that these systems can't be easily pointed so that the actual time they are in the proper position to launch, is very narrow and may not occur many hours or even weeks or days. Also, this number was for a 4kps MT device, which would likely be adequate for some asteroids but will be insufficient for launching from many other bodies including Callisto (which would require about 8kps minimal).

Terraforming Venus

Venus's bane is its extremely thick, hot and toxic atmosphere. As with Mercury, a Solar Occulus or shade is required to substantially reduce the planets temperature. A Solar Occulus that would permit a similar solar radiation as to the earths would require a 50% solar flux reduction. However, to quickly reduce the Venusian temperature, as well as to be able to provide a reasonable day/night cycle we would want an oculus able to totally block the sun for night operations and then permit 50% transmissivity for daytime. However, Venus, has one great advantage over Mercury- near Earthlike Gravity at 91% of the Earths.

One possible advantage of having this thick atmosphere is that Venus atmosphere can be used for aerodynamic deceleration, as well as for cosmic ray protection. One huge challenge is it is over 90x more massive than the Earths, but is not conducive to life as it is mostly carbon dioxide.

Venus Occulus

The British Interplanetary Society proposed a fully occulting shade for Venus that would be about 4.5x the diameter of Venus itself- or $2.5x10^{8}km^{2}$ (Birch, 1991, p. 158). In this scenario, the sun is totally blocked and the temperature of Venus drops rapidly over a timespan estimated as 87.2-200 years. In this scenario the CO2 precipitates out first as rain, creating CO2 oceans, and then snow as the temperature continues to drop (Birch, 1991, p. 159). Besides the extremely large quantities of hydrogen that would need to be imported to create water, the BIS study also postulated an extremely light sunshade material only massing .4g/m2. If such a light material were ever developed the Occulus as well as solar sails become eminently viable. However, as with the Earth Occulus, electromagnetic mass drivers may make launch costs low enough to allow for a much more massive Venusian Occulus. Unfortunately, since Venus has no moon, the Mass Driver would need to be either on Mercury or the Moon, and will need to be much longer to provide the necessary dV to get to the L1 point. Further complicating this is the fact that we need to capture these fast moving payloads when they arrive at our L1 point.

Venus has a very slow rotation, which makes a day its synodic day on Venus last for 116.75 days. However Venus rotates backwards and in reality a full day on venus is 243 days, and the daylight length is 121.5 days. Clearly not acceptable.

Once the temperature of Venus was reduced we could start allowing some sunlight in and could use the same idea as with Mercury- a duel system of Occulator and solar mirror may be needed to provide a more reasonable day/night cycle. However the reality is that we can’t make Venus warm until we remove the excess atmosphere so this will present a substantial challenge to making Venus Earthlike.

Assuming the atmosphere could be eliminated, the daytime Occulus could be like the one at Mercury with two counter rotating disks that would fully open and close every 12 hours. For the case of Venus to give Earthlike conditions we open the occulus to permit 50% of the normal radiation to pass through.

	Position	Size (diameter)	Comments
L1	1,008,000	25,300	100% Shade with Panels or Iris
L2	1,014,300	13,000	90% reflectivity and reflects 650W/m2 to surface

Table 15-3

With the Venus Occulator, if we had a thin shade about 25300km in diameter, it would be able to spin around its center about once every four days if we used aluminum and limited the tension strength to about ½ the ultimate.

As was noted in the BIS study, the massive atmosphere can’t be quickly removed. We can either condense the CO2 out or freeze it into ice. If we condensed it it would fall as liquid rain and pool in lower areas. If spread across the whole planet the CO2 “Ocean Depth” would average about 900 meters. This is about 1/3 of the average ocean depth (2700 meters) on earth, so it implies that sizeable parts of the Venusian surface would become dry land- and the rest a CO2 ocean. To maintain this liquid ocean, the temperature would be between about 217-304k but actualy much closer to the lower number as we would need to maintain a CO2 partial pressure atmosphere of 5.11atm and greater. Nitrogen alone is about 3.2bar so with the CO2 we would have a total atmosphere of over 8.3 bar, and probably much closer to 10. If we lower this pressure the CO2 will boil off and the atmosphere would stay far to dense. Once we go below 304k, we will start to reduce slowly the pressure and we will have rain, but our pressure will still be far to high. At about 217k the planet would now have a 8.3 bar atmosphere of about (3.2 bar N2 and 5.11 bar CO2), Above this temperature the pressure will rise rapidly so that at about 220K we will have a total atmospheric pressure of around 10bar.

This sort of terraforming is feasible now as the technology is essentially just a large sunshield. A little more challenging is creation of the mirror, but the L2 mirror will not be needed until the cooldown occurs- so not for a couple of hundred years. Assuming a complete shade, a quick estimate of the time required to radiate the heat away from the atmosphere can be done by assuming that Venus radiates as a black body and assuming :

$$F = \sigma T^4$$

$\sigma = 5.67x10^{-8}\, W/m^2/\, K^4$

Power radiated:

$$P = FA$$

Where

$$A = Surface\ Area\ of\ Venus = 4.6x10^{14}$$

The amount of Energy that needs to be released through a given area that is stored in a given kg of mass is the equation:

$$E_{per\ m^2} = mc_p\Delta T$$

Where $c_p = Specific\ Heat\ (^J/_{kg}\, C)$- Common values can be found at the Engineering Tool Box (The Engineering Toolbox, n.d.).

$$t \approx \frac{E}{P}$$

Using our current temperature and

We could lower the temperature to below 216k, and this will cause the atmosphere to go from a gaseous to solid phase, and our CO2 partial pressure will continue to drop. The “Oceans” would also start to freeze from the bottom up. We would keep some CO2 in the atmosphere but if we continued to lower it some more even this will freeze out, finally leaving only a 3.2 bar Nitrogen atmosphere behind. The liquid oceans will likely take a few decades to freeze and since solid CO2 is more dense than liquid the “Ice” would be on the order of 640m thick if spread across the whole surface.

Venus would then need to be maintained at these low temperature, otherwise the CO_2 would quickly melt and be released back into the atmosphere. Venus would need to be kept at about 160k (110C). and this would leave you with a 3.2 bar Nitrogen Atmosphere.

Chapter 16 – Colonizing or Terraforming The Outer Planets, Galilean and Saturnian Satellites

Io and Europa

Both these planets are deep within Jupiter's gravitational and radiation fields. Both moons pass through Jupiter's intense radiation belts in every orbit. Io, in particular, is exposed to very high levels of radiation that are very difficult to shield against. It is possible that if some resources are found that it may be worthwhile to have an automated mining station on Io, but it would be far to dangerous and difficult to allow humans to work there.

Europa is slightly more conducive to human existence- it is further out from Jupiter and spends proportionally less time in the highest radiation zone. Colonies could exist under the surface under perhaps 10m below the surface. However approaching spaceships would still pass through the dangerous radiation belts on their way to landing on Europa.

Terraforming Ganymede and Callisto

By almost all measures, terraforming Ganymede and Callisto will be easier or more worthwhile than Io or Europa. Approaching spacecraft that use Jupiters atmosphere for slowing down will pass through the intense radiation belts so the human crew will need to be sequestered in a radiation storm cellar, but a properly planned approach should mean only a day or two in the most intense part of the radiation belt. Once arriving at Ganymede or Callisto, the radiation levels will be lower than that found on Io or Europa.

Ganymede and Callisto are both very massive, but due to their high proportions off water ice, they are not very dense.

	Ganymede	Callisto	Comments
Diameter	5268	4821	
Mass	$1.48x10^{23}$	$1.08x10^{23}$	
Density	1.94	1.83	
Gravity	1.43	1.24	
Escape Velocity	2.74	2.44	
Distance From Primary			
Length of Day	7.15days	16.7days	
Average Surface Temperature	-163	-139	
Atmospheric Density	Negligible	Negligible	

Table 16-1

Terraforming Titan

Titan has the following Specifications:

		Comments
Diameter	5150	

Mass	$1.345x10^{23}$	
Density	1.88	
Gravity	1.35mps/14% Earth	
Escape Velocity	2.64	
Distance From Primary		
Length of Day	15.9days	
Average Surface Temperature	-183	
Atmospheric Density		

Table 16-2

Titan is in many ways the easiest planet to terraform. Its atmosphere is considerably thicker than earth's and is mostly nitrogen. Titan's primary issue is that sunlight is very weak, leading to extremely low temperatures- a bracing -180C. The high pressure, dense atmosphere means that a relatively lightweight space suit that primarily provides protection from the intense cold along with a helmet/mask that provides oxygen would be sufficient. A lightweight suit would be relative, as the thick atmosphere and extremely cold temperatures would tend to carry body heat away very rapidely- muchy faster than the average day in Antarctica.

Besides eliminating the need for a pressure suit, the thick atmosphere serves as an effective cosmic ray shield. However, the thick atmosphere combined with low gravity (14% of earths- less than the 16.6% earths gravity on our moon), mean that running on the surface of Titan will be challenging- it would be like moving through water. Conversely, the low gravity but thick atmosphere means that aircraft and helicopters would be very effective on Titan- thought likely not be able to travel fast.

Titan can never be a warm planet, as it receives only about 1% of the solar radiation that the earth receives. The sun's apparent magnitude would be about 21.8 magnitude- or a little more than 1000lux. Furthermore, the deep and opaque atmosphere means the surface is even dimmer. In addition, this low light level, while more than adequate for vision, is insufficient to permit plants to grow- most plants need 15,000 to 35,000 lux to grow. Titan's day would is the equivalent of 15.945 days which would provide an additional challenge to growing Earth plants, though this is about half of the lunar day so will be easier to adapt genetically modified plants to these conditions. Furthermore, even if possible, heating the planet to above freezing would release vast amounts of volatiles, further thickening the atmosphere, but would also cause the frozen surface to begin melting…if sufficiently warm Titan would be a water world with a tremendously thick atmosphere. Nevertheless, methane, a powerful greenhouse gas, represents almost 5% of the atmosphere of Titan and permits its temperature to be about 12C higher than it would otherwise be.

With an abundance of Nitrogen, Titan atmosphere could be the source of Nitrogen for other worlds- it has more Nitrogen than the earth. Titan could export the excess Nitrogen in order to reduce the pressure while replacing portions of the removed Nitrogen with Oxygen and perhaps strong greenhouse gases to raise our temperature to a less brutal -50C or so. One thing that would have to be monitored during any addition of oxygen to the atmosphere, as the ethane and methane there, as well as any additional hydrocarbons released when the planet is warmed up, can catch fire.

Titans thick atmosphere would make exporting Nitrogen difficult using a MT or Mass Driver- aerodynamic friction and loads would make this form of export problematic. However, if Oxygen were processed and liquified from the water, and methane liquified from the atmosphere, fuel for large ships would be virtually unlimited.

Colonizing of Jupiter Saturn, Uranus and Neptune- Is it possible?

None of the outer planets (Jupiter, Saturn, Uranus or Neptune) have a what would be traditionally regarded as a solid surface. With all, the only colonization that would be possible would be to construct cities that would float in their atmospheres. These floating cities, would resemble a combination of dirigible, hot air ballon and submarine due to their high mass and robust structure.

On earth, a dirigible is filled with the same atmospheric pressure as the surrounding air. It derives its lift from being filled with either hydrogen, or more commonly now, helium. These two gasses are much lighter than the average mass of the surrounding atmosphere, which is mostly Nitrogen and Oxygen. A submarine on the other hand will float because it is a sealed bubble of air at near atmospheric pressure, while the liquid water around it is much more massive than the combined mass of the submarine structure and the bubble of air that is being displaced. On the gas giants, the floating cities would exist in a large sea of atmosphere so will not have the advantage of floating in a dense liquid. Furthermore, the elements in the local atmosphere will have a high proportion of light elements like helium and hydrogen, making a large dirigible like device filled with hydrogen or helium less effective. Furthermore supporting a large city with a flimsy structure like a dirigible structure is not practical for a permanent city. For this reason it is more likely that our floating structure would be made of large steel spherical vessels at near ambient pressure and filled with ambient atmosphere at elevated temperature- more like a hot air ballon. Since the air inside the vessels is heated, its atmospheric pressure is maintained by temperature which reduces its internal mass allowing it to float. To see how much lift we get we need to familiarize ourselves with a few concepts:

Boyles Law

Equation 16-1 $PV = Constant$

Or

Equation 16-2 $V \propto \frac{1}{P}$

Charles Law

Equation 16-3 $V = Constant\ T$

Or

Equation 16-4 $V \alpha T$

Finally we can summarize all the properties of a gas with the equation:

Equation 16-5 $pV = nRT$

Where

$$p = pressure\ in\ Pa$$

$$V = Volume\ of\ gas\ in\ m^3$$

$$n = Amount\ of\ substance, in\ moles$$

$$R = ideal\ gas\ constant$$

$$T = temperature\ in\ kelvins$$

Jupiter, for all practical purposes, would not be viable to build a floating city. As the most massive planet, its escape velocity (from the tops of its clouds) is nearly 60kps- far higher than the capability of any current or planned rockets. Furthermore, the gravitational force on a floating city would be extremely high for humans- about 2.528g. Besides the questionable ability for humans to survive for extended periods of time at this high gravity, it will also effect the mass of the floating city… the city would need to be extremely strong to withstand the high gravity and its larger mass and the higher gravity will tend to make any floating city deeper into the atmosphere where ambient pressure would be very high and even more challenging to reach.

Saturn would also be extremely challenging -a rockets escape velocity from the cloud tops would need to be on the order of 35kps- a challenging number- though much more achievable than Jupiter's.

Neptune's is marginally better and may eventually be achievable. With its escape velocity at about 24kps, but this is still very high and the higher gravity present at the cloud (1.065g for Saturn and 1.14g for Neptune) but it is about 1/3 less than Saturn's.

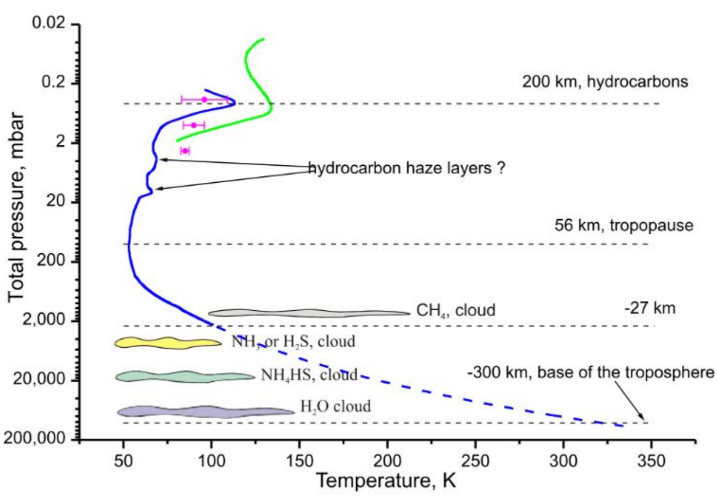


Figure 16-1 The Atmosphere of Uranus

Of all the outer planets, Uranus has the greatest potential to support humans. Uranus, while also a massive planet with a deep gravitational well is still less than the previous three… a rocket leaving from the tops of its clouds would need about 21kps dV- still high but over 10% less than required for Neptune. In addition, the planets density is so low that its cloud top gravity is only about .866g. These two factors could make it marginally more practical to build a floating city.

Assuming we wanted to build a floating city in the atmosphere of Uranus, Saturn or Neptune- what would it look like?

For planning purposes let us pick Uranus for our city and give is a floating mass 10 million mt. This is about the mass of 90 aircraft carriers. The city would be placed above (or suspended below) a very large lifting sphere(s). The city would probably consist of a flat bottom and a large dome mounted on top of the lifting sphere(s)- with the internal pressure of the dome a few percent higher than that within to ensure the dome does not fill with Hydrogen/helium in the case of a leak. Under the dome the buildings, parks etc would be located. The floating support sphere(s) would be maintained at one atmosphere- equal to the ambient air pressure. The city would float in the Troposphere, where pressures range from 100 bar to .1bar. At about 1 bar, the temperature is about 80k (about -197C) (see Figure 16-1). The city domse atmosphere would be equivalent to earth atmosphere- 79% Nitrogen, 21% oxygen. The supporting sphere(s) will be filled with ambient hydrogen/helium heated up above local temperature.

Both the city and the supporting spheres are heated by waste heat from large nuclear reactors. Our target temperature for our sphere pressure is 279K (0C). Unfortunately, the atmosphere of Uranus at this altitude is almost all Hydrogen with some helium which means the displace mass of the gas is very low. This drives the requirement for a very large support sphere. Using the ideal gas law (Equation 16-6) we can calculate how large our spheres need to be:

Equation 16-6 $V = nRT/P$

Where V= Volume

N= number of moles

R= Ideal gas constant

T= absolute temperature (Kelvin)

P= Gas Pressure

Calculating for density using an internal temperature of our sphere of 0C and the ambient air being at -197C our density inside would be .114kg/m3 and outside .408kg/m3 giving us about .294kg/m3 difference. This would give us the following lift per m3

$$\frac{F_b}{V} = \Delta pg = .294x8.7 = 2.56N/m^3$$

Suppose we were to build a floating city of 10 million mt, or 10^{10} kg a $\Delta\rho = .294$

Calculating for V:

$$V = \frac{m_{payload}}{\Delta\rho} = \frac{10^{10}}{.294} = 3.4x10^{10}$$

Or about 4km in diameter. 1.5million mt for our city. If made of 10mm thick aluminum this would mass 1.37million mt. Adding additional mass for stiffeners and joints as well as some margin we might make this to about 3 million mt. This means that our sphere could support a city of about 7 million mt. At the gravity of Uranus, this means I can have 640kg/m2 spread out over a disk 4 km in diameter. This means that at even at 1 bar, we may be able to build a city.

One of the biggest challenges would be getting the raw materials for construction. Whether there are sizeable sources of metal within the Uranus system is unknown. Furthermore, a practical consideration is do we generate enough power to heat and maintain the sphere at this temperature?

Hydrogen/Helium has a much higher conductivity than normal air. Our sphere would have a surface area of $5.03x10^7m^2$.

With a convective heat flux estimated at $q_{conv} = h\Delta T$ and assuming $h{\sim}20 \,{}^{W}/_{m^3}$we will radiate 3940 W/m3. This means to keep the sphere at its elevated temperature we will need a total of $2x10^{11}$W- an extremely large reactor to generate 2TWt. Using our rule of thumb for a non-optimized reactor that puts out 20W/kg, our reactor would mass 10 million mt. However, this factor was for Watts electric and we want watts thermal. Converting this to thermal mass we would use 60W/kg as our rule of thumb. This will reduce our reactor mass to 3.33 million mt. This is still too high requiring truly large reactors so we will require some of insulation. With moderate insulation, we could reduce our heat loss by 75% which would reduce our power plant to 50GWt (still large) massing .833million mt. Compartmentalized panels of insulating gas could provide this improvement. Replacing this with vacuum panels could reduce the heat loss to 10GWt or lower.

In short, a large floating city can be built on Uranus, but it will need a large amount of power, and the challenges of dropping the vast quantities of material into the atmosphere to construct our city would be formidable.

Note finally that we can do endless iterations and tradeoffs. If we sank our city further down into the atmosphere the pressure would increase, increasing the atmospheric density. In this case, maintaining our same difference between sphere inside and outside temperature, we will get more lift per unit of volume. We could also consider increasing the spheres temperature, but a point of diminishing returns is encountered, and the amount of heat needed to raise the temperature is substantial. Building lighter but equally powerful nuclear reactors would aid in whatever design we chose.

In conclusion, building a floating city in the atmosphere of Uranus is possible, but there are several challenges- rocket ships with more than 21kps dv capabilities as well as the challenges of building such a large, massive city including a buoyance sphere over 8km in diameter.

This initial review indicates the city will have the following characteristics:

- Location: 1 bar region of atmosphere, ambient temperature about 80k.
- Material: Sphere will be made of aluminum and about 8km in diameter
- Sphere temperature will be maintained at about 273k.
- Sphere will need to be insulated to reduce heat loss. Goal would be 1W/m2 heat loss which would require a 10GWt powerplant.
- City size: City will be about 4km diameter with a live and deadload rating of 640kg/m2
- City configuration: single dome about 4km in diameter positioned above sphere
- City dome will be pressurized to 1bar with nitrogen/oxygen atmosphere
- Sphere will be manufactured in space in orbit around Uranus and dropped down into atmosphere. Ablative material will coat sphere to protect aluminum during reentry.
- Materials would preferentially be obtained from titania, as this is the largest Uranian moon with highest rock fraction (density).

The dV required to launch a payload from the surface of Titania so that it drops into Uranus' atmosphere is a little more than 3kps. This is because even thought Titania is the largest moon of Uranus, it is still very small with a surface gravity less than 1/26ths of earths or .38m.s2 and the its orbital velocity around Uranus is only about 3.65kps. This relatively low number means that it is within the capability of either an MT or Mass Driver device to launch materials from Titania's surface into the Uranus atmosphere.

$$\Delta v_{\downarrow} = v_c\left(1 - \sqrt{\frac{2\,r_p}{a + r_p}}\right)$$

$$\sqrt{\frac{2\,r_p}{a + r_p}} = \sqrt{\frac{2 \cdot 3.0 \times 10^7}{4.36 \times 10^8 + 3.0 \times 10^7}} \approx 0.359$$

$$\Delta v_{\downarrow} \approx 3.65\,(1 - 0.359) \approx 2.34\ \mathrm{km/s}$$

Titania		Comments
Diameter	1578	
Mass	3.45510^{21}	
Density	1.68	
Gravity	.371	
Escape Velocity	.765mps	
Distance From Primary	435910	
Length of Day	8.7 days	
Average Surface Temperature		
Atmospheric Density	None	

Table 16-3

Neptune and Triton

Of all the moons of Uranus and Neptune, Triton is far and away the most massive and therefore has the highest potential for development. In addition, due to significant tidal heating earlier in its history, its core is substantially warmer than would be expected of a body this small.

Triton		Comments
Diameter	2706	
Mass	$2.14x10^{22}$	
Density	2.06	
Gravity	.78	
Escape Velocity	1.45	
Distance From Primary		
Length of Day	5.9days	
Average Surface Temperature	-235	
Atmospheric Density	.014-.019mbar	

Table 16-4

With that being said, other than distance from the Earth, Triton offers few advantages over other Kuiper Belt objects like Pluto. Triton, as with Pluto, has large quantities of Nitrogen deposits frozen on the surface. Since a Cloud city would be less likely in Neptune atmosphere, it is less likely to be used for resources.

Chapter 17 - Building a Planet

In this chapter we will look at a concept even more challenging and far fetched than Terraforming- building a planet from scratch. This is more for speculative entertainment than realistic option but address if it is possible and if so, how hard would it be? As you can imagine it would be VERY HARD- but not impossible.

Advantages

In the classic (albeit unrealistic) book the Little Prince, the titular character lives on a small asteroid. While the image of living on a small asteroid or moon is appealing, the extremely low gravity of a such a world mean an incredibly low surface gravity (likely low enough that you could jump off the surface and never return). Such a body could not retain an atmosphere for a time longer than a few minutes.

The equation for gravitational force is:

Equation 17-1 $F = G\frac{m_1 m_2}{r^2}$

The gravity on the surface of a planet is determined by its total mass and the distance from its center. If the earth were denser but retained its same volume, its gravity would be correspondingly greater. To calculate the surface g with a assumed uniform sphere of density ρ we use the equation:

$$g = \frac{GM}{R^2} = \frac{4}{3}\pi G\rho R$$

$$R = \frac{.75 g_{Earth}}{\frac{4}{3}\pi G_p}$$

$$M = \frac{4}{3}\pi R^3 \rho$$

Figure 0-1 shows what the diameter of a body with earth equivalent gravity would need to be for various densities. The Earth's has a density of about 5.5134g/cm3 and a diameter of about 12,756km. If the earth had a specific gravity of about 7.9 then it would need to be only about 8920km in diameter and would be only about 50% of its present mass. The figure shows the diameter of a body of various density if we wanted to keep the gravitational forces equivalent to earth gravity. This is a tremendous simplification as the average density of the earths crust is about 2.7g/cm3, but the inner core Nickel/Iron core is close to 13g/cm. Every material has its own modulus showing how it compresses, but in the case of Nickel/Iron, the density of

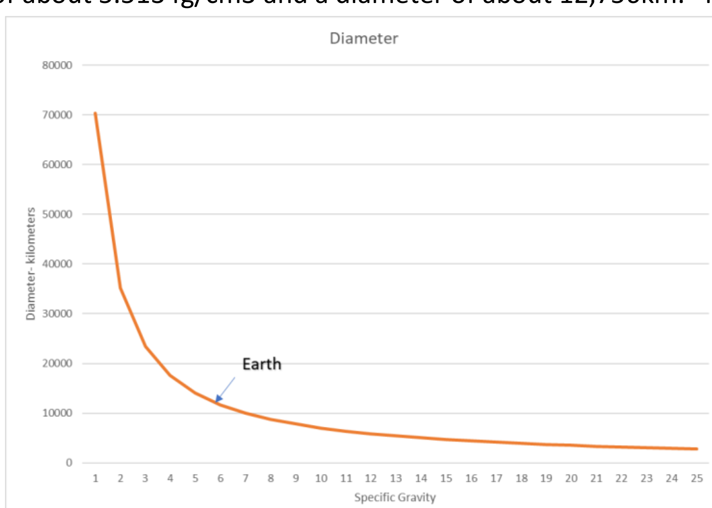


Figure 17-1

iron would range from about 7.9g/cm at the surface to 13g/cm3 at the core where pressure is 360GPa. A solid Iron Earth, with compression at the core, diameter would be about 6400km. In reality, if the mantle and crust were stripped off the earth, you would be left with a planet only 1/3 the mass of the earth but with gravity approaching 1g.

The densest of the naturally occurring materials is Osmium with a specific gravity of 22.59g/cm^3. Unfortunately, Osmium, like many other of the densest materials, is very rare. With a large enough body there would be some gravitational compression, different materials compress a different percentage. Osmium has limited compression compared to Iron. Nevertheless an Osmium planet would only be about 3000km in diameter and mass about 6% of the earths mass.

The densities and prevalence for some materials are listed below:

Element	Density g/cm3	Prevalence (%)	Lunar Mass	Comments
Water	1			Oxygen/Hydrogen
Iron (Fe)	7.8	35		
Silicon (Si)	2.329	15		
Magnesium (Mg)	1.74	13		
Nickel (Ni)	8.9	2		
Sulfur (S)	2.07	2		
Calcium (Ca)	1.55	1.5		
Aluminum (Al)	2.7	1.4		
Sodium (Na)	.97	.3		
Chromium (Cr)	7.19	.2		
Phosphorus (P)	1.82-2.69	.1		Density depends on Allotrope
Titanium (Ti)	4.51	.1		
Potassium (K)	.86	.1		
Manganese (Mn)	7.21	.1		
Cobalt (Co)		.05		
Carbon (C)	1.8-3.51	.05		Density depends on Allotrope
Vanadium (V)		.02		
Zinc (Zn)		.02		
Copper (Cu)		.01		
Tungsten	19.25			
Gold	19.32			
Osmium	22.59			

Table 17-1 Earth Bulk Composition

To minimize the mass of materials needed our artificial planet we would want the densest materials available. What materials would this be? Using Table 47 it looks as if our best materials would be iron and nickel. In theory, a pure iron world with .75g and an average of the density of compressed Iron of around 8.75g/cm3, would be only about 16% of the Earths mass, or about 9.75x1023kg. This is about thirteen times the mass of the moon.

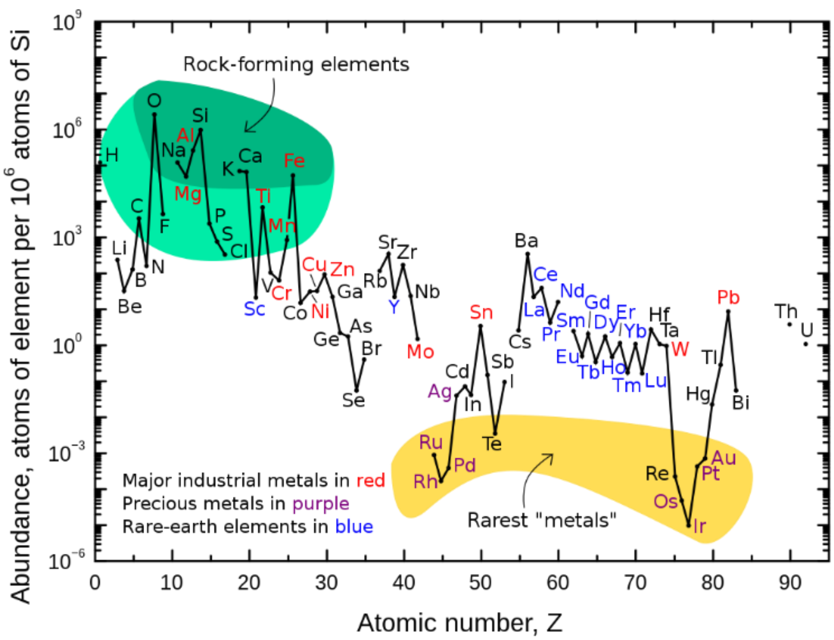


Figure 17-2 Abundance of Elements in Earth's Crust

The earth itself contains most of the original material from the solar system formation with the exception of those materials that were too light to be captured by the earth's gravity and were driven off by radiation from the new sun. The earth is there for depleted in certain volatiles- primarily hydrogen, helium, neon, nitrogen, and carbon. Similarly, the items in the asteroid belt which formed relatively close to the sun would also be depleted in these elements. However, in the colder reaches of the solar system or on the larger planets (Jupiter, Saturn, Uranus and Neptune) a greater proportion of all these primordial elements would remain. The most prevalent solid elements in the solar system that we can build a world out of while keeping our mass lowest would be Iron and Nickel.

The primary advantages of building a world from scratch would be:

- Tailoring the gravity
- Tailoring the location
- Durability and stability. A large planet in a stable orbit can exist for many hundreds of millions of years requiring little intervention.

These advantages would be more than offset by the challenges.

Methods and Challenges

The amount of material needed to build a planet is substantial- and the quantities discussed will be many orders of magnitude more than volumes currently handled annually across the whole globe. Nevertheless, a quick analysis indicates that there is a enough material spread throughout the solar system to build several artificial worlds.

If we were to look at all the moons in our solar system (including the earth's moon) the aggregate mass are about 8.5x greater than the earth's moon. Table 17-3 shows an estimate of the volume of materials available from the various moons (it should be noted that the six largest moons- Ganymede, Titan, Callisto, Io, Moon, Europa and Triton make up over 95% of the aggregate masses of all the moons in the Solar System). It takes the assumed solar nebula content from Table 17-2 and makes some adjustments to take into account that some of the moons were either formed fairly close to the sun or their host planets, and would have experience sufficient heating to drive most of the volatiles away, leaving the remaining materials enriched. Indeed, removing all of the helium, reducing the amount of Neon, Nitrogen, Argon to just traces, as well as assuming that most of the hydrogen is tied up with Oxygen, and making an assumption that the average water content for all moons is around 30%, will drastically enrich the percentage of non-volatiles by about 90x. Note that many of the largest moons (Callisto, Ganymede, Titan) are 50% or more water, but other moons (our moon and Io in particular) have virtually no water.

As can be seen from this analysis, we could probably build a moderate sized planet if we were to disassemble all the moons and reassemble them. We could just take the 8.5 moons worth and lump them into a single planet that would mass about 10% of earth. Such an artificial planet would likely have a density of about 3g/cm^3 and would be about 7400km in diameter. Its surface gravity would be slightly less than Mars at about 3.1m/sec^2. By stripping off the lighter materials and only keeping the Iron and heavier elements (Iron and heavier) we would have a body a little more massive than the moon but with a density of about 8.5 g/cm^3. Such a world with a gravity about 40% of earth or a gravitational acceleration of about 4.2m/sec^2.

Nuclide	A	in parts per million	in parts per million
Hydrogen-1	1	705,700	909,964
Helium-4	4	275,200	88,714
Oxygen-16	16	9,592	477
Carbon-12	12	3,032	326
Nitrogen-14	14	1,105	102
Neon-20	20	1,548	100
Other nuclides:		3,616	172
Silicon-28	28	653	30
Magnesium-24	24	513	28
Iron-56	56	1,169	27
Sulfur-32	32	396	16
Helium-3	3	35	15
Hydrogen-2	2	23	15
Neon-22	22	208	12
Magnesium-26	26	79	4
Carbon-13	13	37	4
Magnesium-25	25	69	4
Aluminium-27	27	58	3
Argon-36	36	77	3
Calcium-40	40	60	2
Sodium-23	23	33	2
Iron-54	54	72	2
Silicon-29	29	34	2
Nickel-58	58	49	1
Silicon-30	30	23	1
Iron-57	57	28	1

Table 17-2

However, while I could see some materials used to build an artificial planet being sourced from the moons, there our better and larger resources available. Most of the various moons will instead provide the metals, water and in the case of Titan, Nitrogen for space stations and terraformed moons/planets.

Element	Prevelance In Solar Nebula (ppm)	Prevelance in Solar System Moons (ppm)	% by Mass	Equivalent Moon Mass %
Hydrogen	705,700	37,500	3.75%	0.3178
Helium	275,200	0	0.00%	0.0000
Oxygen	9,592	420,000	42.00%	3.5594
Carbon	3,032	204,887	20.49%	1.7364
Nitrogen	1,105	22	0.00%	0.0002
Neon	1,548	15	0.00%	0.0001
Silcon	710	63,971	6.40%	0.5421
Magnesium	650	58,565	5.86%	0.4963
Iron	1,260	113,526	11.35%	0.9621
Sulfur	396	35,680	3.57%	0.3024
Aluminum	69	6,217	0.62%	0.0527
Argon	77	2	0.00%	0.0000
Calcium	60	5,406	0.54%	0.0458
Sodium	33	2,973	0.30%	0.0252
Nickel	49	4,415	0.44%	0.0374
Silcon	57	5,136	0.51%	0.0435
Miscellaneous	462	41,626	4.16%	0.3528

Table 17-3 Resources Available from all Solar System Moons; Assumptions- 30% water by mass; 90.1x enrichment; 8.4743 lunar mass equivalent.

The asteroid belt resources are also far too small to build a world- the total mass of the asteroid belt is believed to be only 3% of the moon. Table 17-4 shows a quick and dirty estimate of the volume of materials available from the asteroid belt. It takes the assumed solar nebula content from Table 17-2 and makes some additional adjustments to take into account that the asteroid belt formed relatively close to the sun so that most of the volatiles have been driven away leaving the remaining materials enriched. Removing all of the helium, reducing the amount of Neon, Nitrogen, Argon to just traces, as well as assuming that the hydrogen is tied up with Oxygen, and finally making an assumption that the average water content in the asteroid belt is 20%, will drastically enrich the percentage of non-volatiles by about 95x. The asteroid belt is ideal for providing the metals, and regolith for radiation shielding for building space stations.

I made similar adjustments with Kuiper Belt (Table 17-5) and Ooort cloud material (Table 17-6) prevalence except that the water content was changed to 45% for the Kuiper Belt and 50% for the Oort cloud. Many objects in the Kuiper Belt and Oort cloud have higher percentages of volatiles, but the larger objects, in particular objects like Pluto and Triton (both assumed to have been Kuiper Belt objects) as well as Eris with a density of over 2 g/cm^3 indicate fairly large component of rock.

The Kuiper belt is believed to have between 20 and 200x the mass of the asteroid belt. If we split the range and assume a mass 100x greater mass than the asteroid belt, we would have equivalent material for about 3 moons worth. The Oort cloud is believed to be more massive still- perhaps the equivalent of 5 earth masses (or the equivalent of 406 moons). Using these numbers, we have nearly 31 moons mass of iron between the Asteroid and Kuiper Belt and Oort cloud (almost all is in the Oort cloud). To have a planet with the SG of iron you would need about 38 moon size chunks of mass, which means you almost have enough iron in Solar System to build a planet with earth like gravity. Other factor that need to be considered is that there are nearly 12 moons worth of additional material tied up in miscellaneous elements. Some of these are relatively light, but a substantial

Element	Prevelance In Solar Nebula (ppm)	Prevelance in Asteroid Belt (ppm)	% by Mass	Asteroid Belt Mass vs Luna Mass (%)
Hydrogen	705,700	25,000	2.50%	0.08%
Helium	275,200	0	0.00%	0.00%
Oxygen	9,592	400,000	40.00%	1.20%
Carbon	3,032	217,167	21.72%	0.65%
Nitrogen	1,105	11	0.00%	0.00%
Neon	1,548	8	0.00%	0.00%
Silcon	710	67,805	6.78%	0.20%
Magnesium	650	62,075	6.21%	0.19%
Iron	1,260	120,330	12.03%	0.36%
Sulfur	396	37,818	3.78%	0.11%
Aluminum	69	6,590	0.66%	0.02%
Argon	77	1	0.00%	0.00%
Calcium	60	5,730	0.57%	0.02%
Sodium	33	3,152	0.32%	0.01%
Nickel	49	4,680	0.47%	0.01%
Silcon	57	5,444	0.54%	0.02%
Miscellaneous	462	44,121	4.41%	0.13%

Table 17-4 Resources Available from Asteroid Belt

amount is in heavy items like Nickel, Lead, Gold, Uranium and Platinum.

Finally, having a planet of earth like g is likely excessive. The primary reason for a 1g target is that this is the mass of our planet and the gravity our bodies are accustomed to. Furthermore, this high gravity reduces atmospheric loss to almost zero.

Element	Prevelance In Solar Nebula (ppm)	Prevelance in Kuiper Belt (ppm)	% by Mass	Kuiper Belt Mass vs Luna Mass (%)
Hydrogen	705,700	56,250	5.63%	16.88%
Helium	275,200	0	0.00%	0.00%
Oxygen	9,592	540,000	54.01%	162.03%
Carbon	3,032	152,358	15.24%	45.72%
Nitrogen	1,105	111	0.01%	0.03%
Neon	1,548	77	0.01%	0.02%
Silcon	710	47,570	4.76%	14.27%
Magnesium	650	43,550	4.36%	13.07%
Iron	1,260	84,420	8.44%	25.33%
Sulfur	396	26,532	2.65%	7.96%
Aluminum	69	4,623	0.46%	1.39%
Argon	77	8	0.00%	0.00%
Calcium	60	4,020	0.40%	1.21%
Sodium	33	2,211	0.22%	0.66%
Nickel	49	3,283	0.33%	0.99%
Silcon	57	3,819	0.38%	1.15%
Miscellaneous	462	30,954	3.10%	9.29%

Table 17-5 Resources Available from Kuiper Belt

After colonizing the moon and Mars we may find out that the human body can function very well with somewhat less gravity. Choosing a gravity target of 75% earth (about twice Mars') of about 7.4 m/sec^2, will substantially lower the amount of materials needed. An artificial planet primarily made of Iron and with a density of 8.75g/cm^3 would only need be about 6000km in diameter or the equivalent of 16% of the earths mass- about 9.5x1023kg. . moons mass of iron each. This means we could construct about 3 artificial planets with just the iron present in the Oort Cloud- and 4 planets if including the Nickel.

Where would we place these artificial worlds? Likely we would place them in the space between Earth and Mars. Outside the orbit of Mars sunlight is quite weak and likely insufficient to keep a planet warm even if they had an extensive greenhouse atmosphere. I would conceive perhaps two worlds being constructed at about 170million and 190million kilometers from the sun respectively.

What this analysis shows is that if just considering the available mass, we could build several artificial worlds with gravity that would be comfortable for human existence. However, the actual ability to mine this material, ship it to the appropriate location in the solar system, and reassemble it into a world would be exceedingly difficult and require capabilities many orders of magnitude larger than our total civilization. Furthermore, any such endeavor would likely take many centuries. Currently, just to reach the Oort cloud takes decades. To slightly nudge an Oort cloud body so that it drops down into the inner solar system will not take much of a dV, on the order of a couple of kps. However, it will take nearly a century to drop down into the inner solar system. Furthermore, once it reaches its target orbit distance a relatively large dV will be needed to circularize its orbit.

Element	Prevelance In Solar Nebula (ppm)	Prevelance in Oort Cloud (ppm)	% by Mass	Oort Cloud Mass vs Luna Mass(%)
Hydrogen	705,700	62,500	6.25%	2541.57%
Helium	275,200	0	0.00%	0.00%
Oxygen	9,592	575,000	57.52%	23382.40%
Carbon	3,032	136,440	13.65%	5548.34%
Nitrogen	1,105	553	0.06%	22.47%
Neon	1,548	387	0.04%	15.74%
Silcon	710	42,600	4.26%	1732.33%
Magnesium	650	39,000	3.90%	1585.94%
Iron	1,260	75,600	7.56%	3074.28%
Sulfur	396	23,760	2.38%	966.20%
Aluminum	69	4,140	0.41%	168.35%
Argon	77	1	0.00%	0.02%
Calcium	60	3,600	0.36%	146.39%
Sodium	33	1,980	0.20%	80.52%
Nickel	49	2,940	0.29%	119.56%
Silcon	57	3,420	0.34%	139.07%
Miscellaneous	462	27,720	2.77%	1127.24%

Table 17-6 Resources Available from Oort Cloud

It would be far easier to Terraform Venus than to build worlds from scratch. However, many centuries from now our descendants may decide it is worthwhile. There is enough material to build several reasonably sized worlds.

Chapter 18 - Where Do We Go From Here?

Over the next few years we will hopefully build the basic infrastructure on Earth that will support the initial colonization of space. In this chapter we will review these preliminary steps and the costs involved. In Chapters 20 and 21 we will review and discuss the philosophical, societal and economic challenges of a large space colonization effort.

The building of a permanent human presence depends on systematically building capabilities, both technological and infrastructure. Below is an approximate sequence of events, their technological and industrial readiness, and some time frames. In General the colonization of space will follow this approximate sequence:

Requirement	Needed Development	Time Frame	
Low Cost Access to Orbit	Technological Refinement	Now- 2050	Initial push and expansion of capabilities
LEO Space Stations	Technological Refinement	2035-2050	Tourism and R&D; Artificial Gravity
Initial small lunar colonies for Tourism and raw materials for Large Space Stations	Development of recycling capabilities, high power nuclear; mining and Mass Drivers/MT	2035-2060	Tourism, Science and Space Technology development. Mass Drivers, MT Drivers
Large Space Stations in Orbit and L4/L5	Recycling capabilities and Lunar Resources	2050-2100	
Small Martian Colonies	Recycling capabilities and Martian Resources; high power nuclear	2040-2070	
Large Self Sufficient Martian Colonies	Development of Martian Resources	2050-2100	
Large Lunar Colonies	Development of recycling capabilities; resource mining	2050-2100	
Initial Martian Terraforming		2100-2150	Large mirror to heat up Martian poles and evaporate CO2
Large space stations built around Asteroids		2075-2150	Resource and colonies. Artificial Gravity
Titan Colonies		2125-2200	
Large Scale Terraforming of Mars		2150-2500	Increase atmospheric mass.
Terraforming of Venus		2200-2500	

Table 18-1

Overall Economics and Resource Flows

As was shown in Chapter 2, resources are very abundant in space. Even if items are in relatively low concentrations (like Uranium), the sheer volume of material available means, with enough power, we can extract substantial and virtually unlimited quantities. With that being said, resources on the earth will usually be much easier to extract as the infrastructure for extracting and refining already exists.

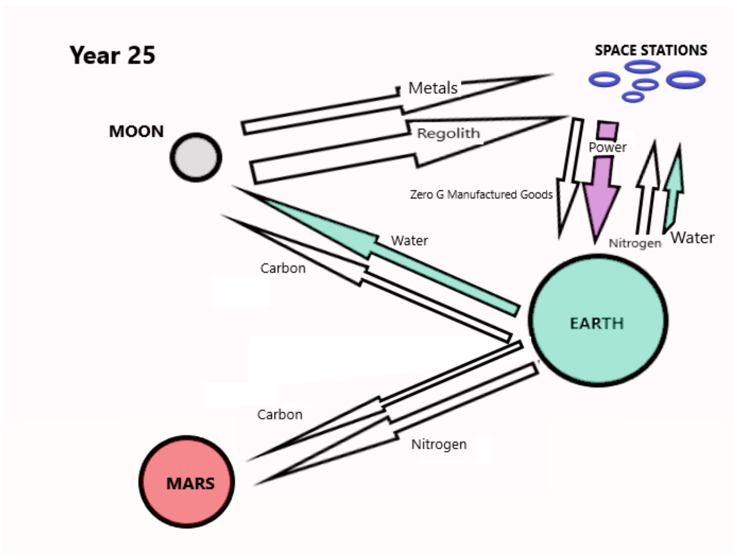


Figure 18-1 2050

However, just as the difficulty of extracting and exporting raw materials from space to earth will keep this business low, for the same reason it is unlikely that large quantities of resources will be shipped from earth over long periods of time. The permanently high costs of earth launch means that as soon as practical, colonists will source required materials locally. As the space economy grows and expands it will evolve considerably. Initially large amounts of materials will need to be shipped from earth to establish the original colonies. The infrastructure to transport large quantities of material throughout the solar system will take decades or centuries to develop. Figure 18-1 shows a notional resource and trade flow (minus the people who will initially come only from earth). During the 1970's it was conceived that the large space stations would, in part, maintain and operate very large solar power stations that would beam their power to earth. Furthermore, these stations would have zero gravity sections for the manufacture of unique products (electronics, materials) that can only be made in zero gravity. These may still be the primary export for at least some stations. In general, the stations will get their people, Nitrogen and Water from the Earth. However, it will probably be vastly more cost effective to get all the structural materials (Iron, Aluminum, Titanium) as well as the Oxygen and Cosmic Ray Shielding (lunar regolith) from the moon. Conversely the moon is very poor in volatiles and colonies will need hydrogen to combine with Oxygen for water, or water may itself be shipped from the earth. Furthermore, the moon is very low in Carbon, necessary for plants and plastics, so at least initially this will be sourced from the Earth. The moon may be able to provide He3 (see chapter 4) to Earth in trade but in general the moon will be a poor source of resources for the Earth.

Mars in general is somewhat richer in volatiles. Mars has its own water (in the form of ice) but like the moon, appears low in Carbon. Some carbon as well as Nitrogen for the initial colonies will likely need to be imported from the Earth, however over time, Mars, and perhaps the moon, will start sourcing their Carbon needs from Carbonaceous asteroids. As industry grows, the space station and colony cities become larger, infrastructure is built out, and humans start going further into the Solar System, we will see the flow of materials change somewhat as shown in Fig 18-2.

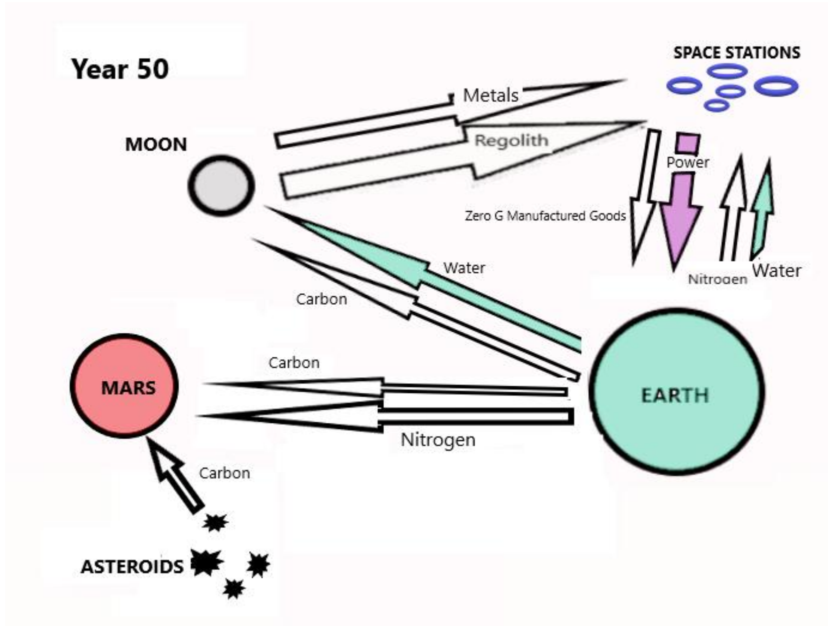


Figure 18-2 2075

Colonization of the moon will require far less support than colonization of Mars. After the first decade or so, most ships to the moon will be for tourists and dedicated missions for equipment and colonizers will be absorbed by the frequent, several times a week, lunar missions.

What will colonization require short term (2025-2060)?

The space colonization effort will likely proceed in the following approximate sequence:

2025-2040

- Weekly manned launches mostly with SpaceX Starship to LEO, Lunar outposts, Mars initial missions
- Orbital Tourist flights (using Dragon capsule and SpaceX Starship)
- Small Space Station(s) to replace ISS and to provide a tourist destination
- Human return to the moon for short duration

2040-2060

- Large Space Station with artificial gravity in Earth Orbit
- Large numbers of space tourists
- Permanent human presence on small lunar outpost
- Construction of GW SBSP Station
- Lunar mining and manufacturing
- Large space station at L5 or L4
- Mars colonization

Other than the development of fully reuseable space launcher, like the SpaceX Starship, the most challenging goal is the Mars colonization. The scope of the Mars colonization (with several thousand missions) is as large as all the other efforts combined. For this reason, let us look at what it will take to colonize Mars.

The Future Markets

High launch costs have restricted the creation of new markets and hence limited the growth of the space industry to the few markets mentioned while lower launch costs have the potential to open up new markets. Some possible markets:

- Tourism (LEO, Moon, L4/L5)
- Space Based Solar Power (SBSP)
- Manufacturing
- Lunar and Asteroid Natural Resources (likely minor)
- Science and R&D

Space Tourism exists now but is high costs (north of $55 million per passenger) drastically limit the numbers of people who partake. A broad and large Tourism industry only becomes possible if launch costs are low enough that vastly more people can partake AND the destination infrastructure is big enough to make it worthwhile to visit. In the next section we will look at some of the requirements and potential of Space Tourism. We will look at tourism market later in this chapter.

In Chapter 12 we looked at the market for Space Based Solar Power. As with Space Tourism, SBSP becomes viable only if launch prices are low enough.

Manufacturing can become a major market if we determine that some very high value products can only be made in the low gravity of space. To date no such materials or items have been identified, but it is suspected that some will be created.

A lot of R&D will need to be done on earth and space to determine what products can be manufactured there and only there. Another area is R&D for items that humans determine are too dangerous to conduct on earth. An example could be to conduct biological research in labs which, unlike those in Wuhan, if a COVID like (or worse) virus was accidentally released, it would not have infected the earth. Similarly, some experiments with nuclear power may be better performed in space. I could envision a scenario where certain industries are banned from the Earth and experiments can only be done in space. However, until these technologies are identified, and until many years of materials experimentation are done, Manufacturing is an indeterminate market and can play an unknown role in our future space economy.

Similarly, while raw materials are abundant in space they are usually available in large quantities on earth and will remain far cheaper to extract. The cost of shipping large quantities of raw materials from space back down-to-earth means only the most valuable elements would be feasible. The one exception is possible Helium3 (see Chapter 6) for possible nuclear fusion plants. This material is almost non-existent on Earth but can be obtained from space, in particular the lunar regolith. Depending on the direction of future Nuclear Fusion development, Helium 3 may be a viable raw material with a market and I will discuss Helium3 extraction in Chapter 6 and 12.

In addition to the possible markets, other less traditional souces of space development will exist with uncertain economic potential and funding. Prime case will be the colonization of the Moon and Mars as well as some of the development at L4/L5. The Mars case in particular will be very massive and is not, primarily, a market. The resources and efforts spent will have to come from rich individuals, and corporate and government sponsorship. Nevertheless, even though these do not count as a market, we need to consider them as they will have a sizeable impact on the development of the space infrastructure.

Tourism

Tourism could be a new market and a major source of revenue. However, the vast distances and their associated transit times mean that Earth tourism, and the attendant revenue, will be limited to only those destinations near the earth. I see the following destinations as reasonable:

- Suborbital hops- strictly for the experience of getting into space for a few minutes. Currently this service is provided by several companies, including Blue Origin and Virgin Galactic.
- Suborbital Ballistic Transportation- able to transport people and cargo anywhere in the world within less than an hour
- Low Earth Orbit visits of 1-5 days
- Earth Orbit visits to a Space Station; 2-14 days
- Visits to the Moon; 4-14 days
- Visits to Large Space Stations at the Earth/Moon L5 and L4 points; 4-14 days

Using a target as a Baseline of $100kg to LEO a future derivative of the SpaceX Starship that can lift 200mt of cargo should cost about $20 million per launch. In reality rocket costs per kg is usually much higher since the full payload capacity is never used, and frequently missions require unique handling that add to our costs. In the case of the Starship, a 200mt payload could carry 2000 people at 100kg each. Unless they were cadavers and stacked like cordwood, this would not happen. Instead, each person will need a chair/acceleration couch, life support (power, air, food, lighting and temperature control), which will make the costs per person considerably higher.

An area of potential revenue is Earth point to point transportation. When Elon Musk expressed the plan to increase the engines on the Starship from 6 to 9, I was not fully clear on the motivation. Even though performance may be slight increased, the additional engines would add weight and complexity. However, the biggest advantage to having 9 engines is that the spaceship can lift off from the ground and enter into a ballistic trajectory on its own. For this reason, I believe suborbital ballistic flights can be done with a Starship or equivalent rocket. Assuming that a full up two stage Starship costs $100kg ($20 million launch price) for orbit, these ballistic hops using only the Starship stage can likely be done for about half this or $50kg and $10million per flight.

Factoring in additional assumptions I see the following costs per person in about 20 years (not adjusted for inflation):

	Duration	Cost per Kg	Total Cost Per Launch	Number of Persons	Per Person Cost	
Suborbital Hops	15 min				$20,000	Short excursions above 100km; currently done by Blue Origin and Virgin Galactic

Suborbital Ballistic Transport	<45 min	$50	$10,000,000	250	$40,000	
Low Earth Orbit	1-5 days	$100	$20,000,000	200	$100,000	
LEO Space Station	2-14 days	$100	$20,000,000	250	$80,000+ $10,000 day	
Moon	2-14 days	$1000	$100,000,000	100	$1,000,000+ $100,000 day	9 Tanker Refills
L4/L5	2-14 days	$500	$50,000,000	200	$500,000+ $50,000 day	4-5 Tanker Refills

Figure 18-3

Suborbital Hops- this will be a mostly separate business from launch providers. However, they are provided as a reference. Currently prices for Blue Origin New Sheppard suborbital flights are not published, but the internet has indicated that costs range from $200,000 to $500,000. However, with greater popularity and the introduction of the Starship, costs will likely drop substantially in the future.

Suborbital Ballistic Transport assumes a single stage only. As such costs should be much less than orbital launches and I assume about 50kg for the same 200mt payload; with 250 passengers works out to $40,000 per person. This will provide a short hop to anywhere in the world within 45 minutes or less. Depending on the growth of infrastructure, and where spaceports are built, this could become an area for future transportation for priority cargo as well as impatient (and wealthy) travelers. These suborbital rockets can also provide tremendous capabilities for the military.

Low Earth Orbit visit- The Starship is a very large vehicle with a large cargo volume. The design is still evolving but it looks to be on the order of 1000m^3. For comparison, the largest version of the Boeing 777 has about 470m^3 of volume and holds up nearly 400 passengers. For a multiday voyage on a Starship, much more volume per person will be required but 200 people is probably a reasonable number for the available volume. At $20 million per launch and 200 persons a flight would work out to $100,000 per person.

Visit to Earth Orbit Space Station- using a nominal $20 million per launch we could also visit a large space station in LEO. Since we are docking with a space station our mission times up and to the station are likely only a day or so, and as a result we can probably have a slightly higher passenger density on our spaceship, perhaps 250 per flight. The Space Station itself will have to be resupplied to handle the passengers but assuming dedicated cargo supply flights, costs of $10,000 per day to include normal amenities as well as to help pay for the capital spent on designing and building the station, should be reasonable.

Visiting the Moon is more challenging and speculative. To travel to the moon and land will require about 9 tanker refills, and using our standard $20million costs our total cost will be on the order of $200 million per mission; however, the Starship would not have enough fuel to take off form the moon and return to earth. I anticipate this to be addressed in several ways:

- Reduces payload and passengers to the moon; I have selected a 100 persons voyage for this reason.
- A Starship optimized for the lunar mission, and with perhaps a slightly lighter empty weight thus improving it dv performance

- Availability of lunar resources. Though the moon totally lacks Methane for fuel, it would be able to provide liquid oxygen. For Methalox engines, the approximate mass of liquid oxygen is 4x greater than the methane so only the methane would need to be carried to the moon for its return flight. Due to the roughly ten times greater costs of traveling to the moon, I also assume that a daily residence at colony will be ten times greater than for the LEO Space Station, or $100,000 per day

Visit to L4/L5. Since we do not need to land on a surface, the dv required to get to the L4/L5 is less than traveling to the moon- I assume four/five refills. In addition, due to the low dv required I assume we can carry more personnel than the Moon visit- in this case I assume 200. If residing at L5, because it is easier to reach than the lunar surface, and can be supplied raw materials from both the Earth and the Moon I assume that the daily residence will be about half those of a lunar stay.

These are very rough ballpark numbers to give an idea of costs and challenges. I have neglected capital costs when developing these numbers. The assumption is that, as with airlines, these costs will be covered over time.

Let us assume that each rocket costs to build $100 million per first stage, and $200million for the second (Starship) stage. These numbers seem extremely low when compared to a commercial airline, but commercial airlines fly for decades for thousands of flights, carry several hundred passengers for each flight. Our Rocket/Spaceship is likely only to be in service for a year or two and most of its structure is a simple tube of stainless steel. A large portion of the rockets costs are its engines, which Mr Musk has been successful in mass producing.

Lets assume that each rocket is good for 100 launches, with $1 million of maintenance between launches. With our launch costs are kept at $20million per launch over 100 launches our revenue would be $2billion. Our Rocket/spaceship would cost $300 million to build, and $100 million to maintain over its hundred flight life. This means the remaining $1.6 billion would be for the consumables, fuel and oxygen, and any other operating costs.

Similarly we can get rough revenue numbers from tourism for the LEO and L4/L5 Stations and the moon. In these cases, the Stations and the Lunar colonies would be very large, and we can assume they could handle a large number of tourists. Assuming that on average, we have 1000 tourists at each, this would equate to:

- LEO Station at $10,000 day: $1 million of revenue per day; $91.25 billion per year
- L4/L5 Station at $50,000 day: $5 million of revenue per day; $182.5 billion per year
- Lunar colony at $100,000 day: $10 million of revenue per day; $365 billion per year

Using an average stay at LEO of 4 days; and an average stay at the moon and L4/L5 of 10 days, we can calculate the total number of tourists and therefore the number of flights per year.

	Average Duration Days	Annual Tourists man days (assume 1000 average tourists per day)	Ship Size	Annual rocket launches	Refueling Flights	Total

LEO Space Station	4	91250	250	365	0	365
L4/L5	10	36500	200	183	732	915
Moon	10	36500	100	365	3285	3650
Total		164,250	**Total Flights**	**913**	4017	4930

Table 18-2

The total tourists revenue are associated both with the launch/return as well as cost of visiting the destination- since, at least in the first few decades, will get a majority of their supplies from the earth.

This shows that for a tourist industry of 164,250 travelers per year, between almost 5000 launches are required, but only a little more than 900 are carrying passengers. On average about 13-14 rockets will be launched per day.

The costs to launch each of the 5000 rockets of $20million per year will lead to revenue of $100 billion per year. In addition, to support the launch and return, and the tourists visiting the LEO Space Station, L4/L5 and the Moon will cost another $640billion for a total tourist annual revenue of $740 billion. This, somewhat arbitrarily assumes a total of 164,250 tourists per year. The average space “vacation” would costs $3.9million. The question is whether our Space Tourism industry has enough high net worth tourists who can pend an average of $3.9 million for a space vacation.

In 2023, using federal reserve estimated that about 1.3 million households were in the top 1% of net worth with over 13.7 million or more of net worth (PK, 2023). The United States has about 40% of the global top 1% of wealth (World Population Reviewe, 2025). This implies that worldwide about 3.25 million households can afford one of these trips. Note these are households, so the number of individuals will be higher. This implies that about 5% of the households per year will have to pay for a ticket to space. This seems very high, but a lot depends on the next few decades of economic growth- if the number of wealthy families and individuals grows faster than cost of a space launch, then the world economy may be able to support hundreds of thousands of tourists per year.

In conclusion, currently it would be challenging to support an annual space tourism industry of hundreds of thousand per year at the future projected average of $3.9million. However economic growth continues to increase the number of rich individuals and it may be possible that within 20-30 years the space tourism industry could generate $640 billion per year in revenue supported by about 5000 annual launches.

Space Based Solar Power

In chapter 12 we looked at the economics of SBSP. Whether this industry is viable is highly dependent on the launch costs but as described, can generate multibillion dollar revenue streams and provide GWe of clean carbon free power to the Earth. A rough estimate was that it would take about 2000 starship launches to build a 10GWe power plant. Will one plant be built, or dozens? It is impossible to speculate but the likelihood is that each plant built will be slightly cheaper than the previous one. If we assume a modest construction of one 10GWe SBSP built every two years, then the launches associated will be 1000 per year. The price of the first unit was estimated at $77 billion but some of this will not go towards the space industry but rather on domestic suppliers. Regardless, our 1000 launches per year will generate $15 billion in revenue. Making a real wag that additional revenue will be from the construction and maintenance crew of $10billion per year, we have revenue of $25billion per year supporting the launch and space construction industry.

As opposed to most resources that will have to be mined and processed, power in space is freely available. It is relatively easy to collect and beam down to the Earth. Nevertheless, the cost of space launches, and the massive size of a large Space Based power plant will make it challenging to justify economically and difficult to engineer and build. In Chapter 12 we saw how big these power plants are and developed some rough idea of the costs involved. Nevertheless, the amount of power that could be collected, and the associated revenue stream will likely make this the most likely export from Space to the Earth.

LEO, L4/L5 and Other Space Stations, and Lunar Colonies

Over the next two decades or so, medium and perhaps large space stations will be built, mostly in LEO but also in L4/L5. The initial stations will primarily be for materials development, engineering testing, and Tourism. Over time, as larger stations are built at L4/L5, they will be sizeable independent colonies in their own right. However, pending the still speculative development of low and zero-g materials, most of the traffic and resource flows to these space stations will be for tourism. The proximity of these stations, and the associated short travel times, makes these, along with the Moon, the only practical destinations for a majority of Earthlings.

Besides tourism, possible source of revenue, depends on the development of Solar Power. These stations will likely provide the majority of the workforce to build and maintain large SBSP.

Lunar colonies, besides being destinations for tourists, will also be a source of some of the raw materials for the large space stations, primarily at L4 and L5. As discussed when building space stations, both metal and the cosmic ray shielding, will come from the moon.

Basic Science, Research and Development

Fundamental science can serve as a minor but important market supporting the colonization of space. Some basic science including astronomy and physics, as well as materials research can be performed in space.

For Astronomy, the lack of atmosphere and/or gravity makes the construction of truly large visual, ultraviolet and infrared observatories, possible. The launch and construction of these observatories can both support rocket launches and support fees of the space colonists. Large observatories can be constructed at L1/L2/L4 and L5 as well as the moon.

The large amounts of resources and available volume or area for construction makes facilities that would be impractical to build on earth possible in space. Basic research that is too dangerous to be done on earth will be much less dangerous in space. The construction of nuclear engines, bio-engineering and large physics experiments like gravity wave detectors (like interferometers) or particle accelerators, can be built. Governments, universities and foundations will depend on launch providers and space based support staff to build and maintain these facilities. On a planet where a single large experiment like the International Thermonuclear Experimental Reactor (ITER) fusion research plant is projected to cost $30billion to construct, or the Large Hadron Collider cost about $10 billion, it is easy to estimate that several billion a year will be spent around the world for launch and support services.

Market Summary

Getting an idea of the market for space is problematic. Much of the revenue created will come from building and launching rockets from earth and providing the service to earth. As such, this is just a continuation of the current business model, with little to help with colonization. The only real assistance is that indirectly the launches being paid for will help subsidize the rocket development and infrastructure that WILL help in our colonization efforts.

For this reason, among others, I will leave this out of our Market summary. Instead I will focus only on large and new industries which will be funded by Companies, Governments and Agencies which will also support colonization by drastically expanding the need for launch services. As has been mentioned before, the colonies themselves will establish their own economy and will not be a part of the Earth funded part. An L5 colony will likely establish its own mining operation on the moon to supply building resources. A Mars colony will be built by the colonists that arrive there and funding from Earth will not be needed once established.

Lumping our proposed "new" Markets to four categories, in 20-30 years here are some reasonable snapshots:

- Tourism- $640 billion per year
- Solar Power- $25 billion per year
- Industrial/Material Science- $5billion
- Space based Basic Science- $5billion

These revenue streams will help fund the development of new rockets, as well as space construction techniques of building large, rotating space stations and colony outposts.

The important highlight is that almost 95% of the projected revenue (as well as about 90% of the launches) will be for tourism. This implies that a large percentage of the development of improved and efficient rockets, as well as the destinations, will need to be tailored toward the tourist. Our target, market driven business in 20-30 years will be on the order of 6000launches per year- or 16.5 launches per day, before the impact of Mars Colonization is added in.

Non-market Colonization Drivers- Mars

By far and away, it appears that the most common launch vehicle over the next ten years will become the SpaceX Starship. The Starship design is constantly evolving, and its performance is changing, however, using the latest published performance for Starship V4, the payload to orbit is projected to be 200mtFor the SpaceX Starship, the fuel/oxygen ratio is 22%/78%. The impetus for the Starship design as stated by Elon Musk is for this spaceship to be the primary means of getting people and equipment to Mars for a colonization effort. With this background let us primarily focus on the economic, environmental and social impacts of Mars colonization.

A summary of Starship (Marship) capabilities are as follows:

	Capability	Comments
Empty Mass (mt)	150/100	Two different empty mass's are assumed

Payload Mass (mt)	200	
Fuel and Oxidizer (mt)	2300	
Total Mass (mt)	2650/2600	
Rocket Engine ISP/mps	363/3.56kms	Stated vacuum capabilities
dV Capability	7.2kps/7.7 kps	Note that some of these are best case performance; assuming atmospheric reentry will slow the rocket down, some fuel will be needed to land- perhaps as little as 1kps

Table 18-3

Elon Musk has indicated a requirement to put at least 1million mt on Mars to create a self-sustaining colony. Assuming that the Mars bound Starship (hereafter called Marship) brings 200mt to the Martian surface, we can calculate how much fuel/oxidizer will be needed. The current plan is that a Marship is launched with its payload and placed into low earth orbit. A series of specialized Starships that are built for carrying fuel will then be launched, rendezvous with the orbiting Marship, and transfer their fuel to it until its tanks are fully topped off. The fueled Marship will light its engines and depart for Mars. Whether a Marship will need to be fully fueled or can get to Mars with somewhat less than full fuel, can only be determined by the final performance figures of the Marship and the date launched and the targeted travel time. Figure 2 is called a porkchop plot that shows the relationship between three numbers- Earth Departure Date vs a Mars Arrival date and the required spaceship performance. The concentric colored contours are various rocket dV's. Essentially the faster you can travel (the colored contours) the faster you can arrive at Mars or, conversely, the wider you launch window is . If your rocket can do 6, 7, or 8 kps, you will only have a four month or so launch window. Looking at Figure 2, if your ship left in May 2018 it would arrive Dec 2018. If however, your rocket could do about 13kps, then leaving in May would allow you to arrive at Mars in August, or conversely you could leave at virtually anytime and arrive at Mars.

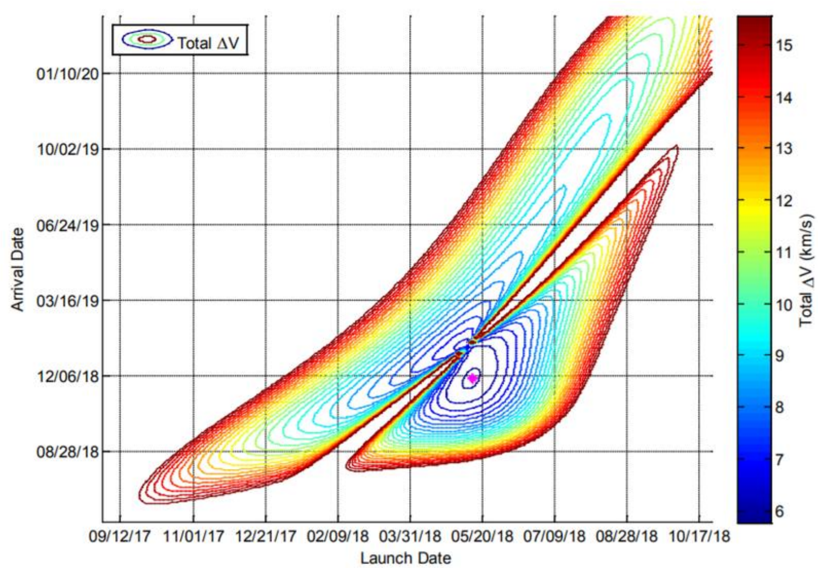


Figure 18-4 Porkchop Plot

Based on the apparent Starship performance in Table 1, our Marship may only be able to do about 7.2kps- severely restricting our velocity and hence launch windows. Furthermore, some of this performance will be needed to land on Mars, making the Starship marginal at best as a Marship. If we assumed a more ambitious empty weight on our Marship of 100mt, then with our rocket equation we can have a theoretical dv of 7.7. Unless we reduce our 200mt payload (which will increase the number of voyages to Mars) this is probably the most we can obtain from our Marship performance.

Assuming every Marship will need to have its fuel tanks fully topped off in orbit, then each will need about 12 refueling tankers for each mission. Every Marship will need about 18,200 of Methane, and 64,350 mt of Oxygen (Table 2). For each metric ton of fuel/oxygen used, only 2.4 kg of cargo actually arrives at Mars…or .24%.

	Marship Earth to Orbit	Earth Orbit to Mars Total (12 refuels)	Landed on Mars Total (13 launches)
Payload	200mt	200mt	200mt
Fuel	1400	16800	18,200
Oxygen	4950	59400	64,350
Total Fuel/Oxidizer			**82,550**

Table 18-4

While this is an extremely simplified analysis it gives a good idea of the magnitude for a Mars colonization. We can make different assumptions that will reduce these numbers. One possible area to reduce the magnitude is to assume that not all Marships will return but some will instead be left on Mars. The ships can be scraped and their materials used for the colony, their mass being added to the payload mass.

To get 1 million mt to Mars, at 200mt payload per ship, equates to 5000 spacecraft to Mars with 60,000 refueling providing the fuel- or a total of 65,000 launches spread out over many years. If we assume 20 years it works out to an average of 3250 launches per year.

The amount of Methane required to get the target 1million mt of payload to Mars works out to about 91million mt. Spread out over 20 years this is about 4.55 million mt of Methane per year. In reality they will not be spread evenly out. The rockets will need to be launched during optimal positioning of Mars and Earth which reoccurs every 26-months. During the 20-year colonization phase we will have about 9 Mars ship convoys… each one consisting of about 356 Mars bound rockets launched (Musk has previously indicated about 1000 for each cycle- thought this may be when he was planning on a Starship that could only carry 100mt). Most of these rockets will need to be launched within a period of a few months on either side of the optimal planetary alignment. Assuming a 4 month launch window a total of about 7220 rockets will need to be launched- or about 1800 per month or 60 launches per day.

The launch cadence required is many orders of magnitude larger than anything previously attempted. Every day about 12,000mt of payload would be orbited… or about 8x greater than what is currently launched per year.

At first glance this appears to be impossible or impractical. However, it should be noted that currently the world has about 100,000 aircraft flights per day that use about 100 billion gallons of fuel annual (Department, 2024). This works out to about 134 million mt of fuel per year. This implies that Mars colonization will be the equivalent of 3% of the fuel currently used by the aviation industry. The challenge with colonizing Mars is that this activity will not be spread out over thousands of airports, and that, as opposed to liquid jet fuel, Methane is frequently transported as a high-pressure gas or kept extremely cold when handled as a liquid. While a natural gas infrastructure is widespread, the gas system as a whole caries a blend of fuels of which Methane is only a part. Many of the spaceports that would need to be built would be fed by pressurized but purified to 100% Methane Gas, or will need purifying equipment at the spaceport. The spaceport can also be supplied via large Liquified Natural Gas Vessels.

The required sixty launches per day would likely not be feasible or desirable from a single facility- the fuel requirements would be astronomical. There are likely to be two or three facilities in the United States (Kennedy/Canaveral, Brownsville and possible Wallops Island) and perhaps several more located around the world- perhaps Mexico, the Caribbean islands, Australia, China or India.

Notional Spaceport

To get an idea of the logistics involved at each launch site, and thereby an indication of the environmental impacts we need to consider a notional starship launch port. For planning purposes let us assume there are 5-6 launch sites across the world, and that each can host 12 launches per day. This should be enough on average to support our target activity. We already figured that our normal market driven activity will be about 16-17 launches per day. During certain periods, we will experience a "Martian Surge" of 60 more launches per day supporting the Mars Colonization.

How big would a notional rocket launch site be? If we assume six launch towers and that each launch tower handles 2 launches a day, a large facility like Brownsville or Cape Kennedy/Canaveral will support 12 launches a day. As space travel becomes more routine we may be looking at each launch tower doing handling even more- perhaps three or four daily launches, but this tempo will likely be decades in the future. Regardless, during surge periods we may be launching up to 77 launches per day between Market launches and Mars colonization. If each space port is able to handle 12 launches, then we will need 7 ports worldwide. This can be reduced if we either expand our spaceport to handle more daily launches, expand our Martian window to 5 months, or if we reduce the Market launches during surge periods. During the non-surge periods we would return to a cadence of 16-17 a day worldwide.

Supplying Methane to the rockets will be a logistics challenge, likely do-able only by having a dedicated pipeline bringing in the fuel. Methane is the predominate component in Natural Gas, typically making up about 87%. It would have to be purified to eliminate other natural gas components. Natural gas is usually delivered via high pressure pipeline from a gas field, or from Liquified Natural Gas (LNG) vessel that would pipe the Methane from a dock into large insulated and pressurized storage Tanks. Large LNGs ships might carry nearly 270,000 m^3- or approximately 120,000mt (Engineering Tool Box, 2008). This is enough for about 85 launches. At our launch rate of 12 per day, we would need about one LNG vessel per week. Large Methane tanks, either tied into a high pressure Natural Gas supply or tied into a LNG Dock, will likely be built within a couple of kilometers of the launch site to store sufficient fuel to support the launch cadence.

Oxygen will likely be made locally from the atmosphere. Depending on the atmospheric temperature, as well as the final temperature you bring the liquified oxygen down to, along with the engine efficiency will determine your exact energy efficiency. Using the following equations:

$$COP_{Carnot} = \frac{Q_C}{W_{el}} = \frac{T_L}{(T_H - T_L)}$$

And

$$W_{el} = \frac{Q_C}{(\eta_{Carnot} COP_{Carnot})}$$

Where η_{Carnot} is our efficiency which I place at .55, T_H is the highest temperature in your cycle, and T_L is the lowest. Using these equations, you will need approximately 213,000 kj/kg to condense oxygen into a liquid state. In addition, typical equipment conversion efficiencies are about 50%. We would need about 426kj/kg. With about 60,000mt of oxygen needed per ship, we would need 23.4×10^{12} joules. This seems accurate… Airliquid has a oxygen liquification plant, Yango that produces one ton of liquid oxygen per 400-600kw/hr (Air Liquide, 2022, p. 46) (Air Liquide Engineering and Construction, 2022, p. 8). To generate 60,000 mt assuming a 400kw/hr efficiency we would need 24 GWe, or 1 GW per hour if spread out over a 24 hour period. This is the power put out by one large nuclear reactor. As with the Methane, large cryogenic storage vessels would need to be built to hold the generated Oxygen until it is needed.

Our notional facility will have 12 launches per day over our four month launch window. I have assigned real rough cost numbers to each of the primary infrastructure elements. To build and support this facility our costs will be:

Facility Costs	**Quantity**	**Costs (in Billion)**	**Comment**
Number of Launch Towers	6	$3	Assume each tower handles two launches and recoveries per day; Costs include flame trench
Methane Tank Storage (mt)	120,000	$.48	7 days supply of Methane; One LNG ship per week will resupply tanks
Oxygen Storage Tanks (mt)	120,000	$.48	2 days supply of oxygen
Site Preparation		$2	Paving, Roads, Water, Sewer
LNG Dock		$1	
LNG Pipeline	20 km	$.5	
Rocket Assembly Buildings		$2	Including assembly, refurbishment and storage of Starships
Passenger Facilities		$.2	Processing, training, cafeteria
Power Plant Costs	2 Reactors	$15	1.5 GWe; assume that dedicated power plants will need to be constructed
Total Initial Costs		**$26.6**	
Recurring Costs (Daily Operating Costs during four month launch window)		**Daily Costs in millions**	
Methane used per day (mt)	16,800		
Oxygen used per day (mt)	59,400		
Electricity required to produce oxygen	1 GWh	$.25	At $.25 per kwh

Daily Electrical Costs for Operations and Methane Chilling	.5 GWh	$.125	At $.25 per kwh; costs for keeping Oxygen and Methane chilled; operating facility and infrastructure
Staff ($150,000 per employee)	5000	$2	Involved with turnaround and refurbishment of rockets; facility operations and maintenance
Daily Operating Costs			
Idling Costs (during non-launch windows)		$1.5	Assume 25% reduction due to less headcount and OT.
Daily Operating Costs			

Table 18-5

Total Development costs of a Starport are about $27 billion- and assuming two large starports in the US, about $54billion. Reoccurring annual costs per Starport be approximately. These numbers are substantial, however, are only a small fraction of the nation's GDP, and well within the capabilities of large companies.

Power Requirements

Our notional spaceport will require a lot of power, during Oxyen production and the chilling of Oxygen and Methane, on the order of 1.5GWh of power.

Summary:

The colonization efforts will require substantial infrastructure that require large supplies of power and Natural Gas. During a four month launch window occurring every two plus years, the launch facility will generate 12 launches a day with 24 attendant sonic booms that will be heard over a large area. These environmental impacts cannot be avoided or mitigated. However, except for the large sonic booms, these facilities will have a smaller footprint than a typical large international airport. Initially, because of the size and requirements to be near water (for sonic boom and launch concerns, as well as the likely need to be resupplied by natural gas vessels) will restrict these launch points in the US to only Brownsville Texas and Kennedy/Canaveral Florida. Additional overseas launch sites may be possible, including islands in the Pacific Ocean, the Caribbean, the coast of Central American etc. Furthermore, countries like China would likely have at least one major spaceport.

Technological Timescales

The following tools will need to be designed and built:

- Large Scale Mining (Moon, Asteroids, Jupiter Satellites)
- Large Scale Transfer of Volatiles (from Venus, Outer Moons)
- Large Scale Moon and Planet Mass Drivers
- Large MT devices at L4/L5 points
- Large Solar Shades (Venus, Mercury)
- Large Solar Mirrors (Mars)
- Large Fission Power Plants (1MWe- 10GWe)
- Large Solar Power Plants
- Large High Impulse Space Tugs

Raw materials for these various colonies would come from:

	Resource needed	External Resource Source	Transfer Method
Large Space Stations at L5	Steel, Aluminum, Atmosphere (Nitrogen, Oxygen), Radiation Protection (regolith)	Earth, Moon	Rocket, MT or MD (moon)
Moon	Water, Nitrogen, Carbon	Earth, Titan, Ganymede (ammonia), Callisto	Rocket (Earth/Titan), MT or MS
Mars	Nitrogen, Carbon	Titan, Venus(Carbon), Phobus/Deimos(Carbon)	Rocket, MT or MD (Phobus/Deimos)
Cyclers	Steel, Aluminum, Atmosphere, Radiation Protection (regolith)	Moon, Asteroids, Titan	MT or MS
Callisto, Ganymede	Steel, Aluminum	Moon, Asteroids, Titan, Pluto	MT or MS
Ceres, Asteroids	Nitrogen	Titan, Pluto	Rocket, MT or MS (Pluto)
Triton and Other Kuiper Belt, Oort Cloud	Steel, Aluminum	Asteroids, Moon	MT or MS

Table 18-6

Realistic Unber Rocket Performance for late 21st century

Most optimistically we may be able to build a fusion rocket that would have extremely high power and thrust output.

Suppose we would issue a contract bid for an ideal passenger spacecraft- what would our specifications call out for? Then let us go with a minimal "ideal" specification for

Requirement	Target	Minimal	
Passenger/payload	100/100	50/50	
Ship total dV	1000kps	100kps	
Ship Acceleration	1 g	.5 g	
Artificial Gravity	1g	.5 g	
Power Supply	1000kw	100kw	Electric (thermal will be about 3x greater)
Radiation Exposure	Equal to Earth	2x Earth	
Crew/Passenger Power Requirements	10000W person	10000W Person	
Voyage Duration	Days to		

Table 18-7

Industrial Timescales

21st Century

- Chemical, Solid Nuclear Thermal Engines, Large Ion Engines

- Lunar Mass Drivers (Metals, Cosmic Ray protection)
- Asteroid Mass Drivers (Metals, Water, Cosmic Ray Protection)
- Small and medium size Stanford Torus designs (up to several hundred thousand people) around Earth
- Large O'Neal cylinders (up to several million people) from lunar resources located at L5
- Lunar caves and Domed Craters
- Lunar Elevator
- Domed Martian Cities
- Mars Cycler- Stanford Torus or Bernal Sphere
- Moderate Martin terraforming
    - Martian mirrors to increase temperature and atmospheric density.
    - Mars Nitrogen importation
    - Gradual increase in Oxygen content
- Large Stanford Torus and O'Neal cylinders centered on asteroids.

22nd Century

- Venus Terraforming
    - Large Occulator
    - Importation of Water
    - Importation of Hydrogen
    - Export of Nitrogen
    - Creation of Oxygen
- Moderate Titan Terraforming
    - Removal of excess Nitrogen in atmosphere
    - Some increase in atmospheric temperature through greenhouse gas
- Ganymede and Callisto Mining and Colonizing
- Jupiter and Saturn Cyclers

23rd Century

- Moon Terraforming- Steel Roof

Chapter 19 - Required and Speculative Technologies

In this book, we have laid out the current and easily extrapolated technologies that will be used in the conquest of space. Technologies like improved fission power, solar cells and marginal improvements in materials are all realistic assumptions. Future technologies required can be broken down into three categories- exist with no new fundamentals and just need to be applied, technologies that can be built with only slight improvements, and technologies that require considerable more work but are believed to be achievable. Table 19-1 gives examples of the various potential technologies, their status and which of these categories they fall in.

Power and Propulsion Technologies

The following technologies are 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 and an even more advanced reactor of 40W/kg which starts making high power electric thrusters feasible. Substantial improvements in the mass efficiency or reactors can be used to improve a space ships performance by making more mass available for payload, reaction mass or our ship structure.

Thorium Reactors

As discussed in Chapter 6, thorium is more prevalent and easier to mine economically throughout the Solar System than Uranium. However, while some test Thorium Reactors have been built, our experience with them is far more limited than that with traditional Uranium fission reactors. Additional engineering design work will need to be done to make Thorium a viable energy source- though the advantages of thorium are so great that it will likely become a common, and perhaps default nuclear power source, at least until Fusion is developed.

While a traditional breeder Thorium Reactor might not be suitable for compact fission reactor solid fuel ^{233}U can be used with a similar traditional fission reactor.

Fusion Reactors

Relatively lightweight fusion reactors for power would be a game changer, especially if they do not require He3. This is because, while fission reactors can provide many of the same benefits of Fusion, fission reactors rely on relatively rare and difficult to obtain Uranium or Thorium.

Fusion that can use normal hydrogen means that fuel will be abundant on almost all worlds except for perhaps Mercury and the Moon.

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. The issue with these types of rockets (besides the design challenges) is the fact that use tremendous amount of fissionable fuel and their exhaust is highly radioactive meaning their uses will be restricted.

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 NSWR 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 (Zubrin, Nuclear Salt Water Rockets: High Thrust at 10000 sec ISP, 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 three primary drawbacks. As with other liquid and gaseous core engines, its exhaust is highly radioactive because the nuclear material is not contained. The second issue is that it is speculative as it has never been built and several engineering problems would have to be addressed before we can determine if this can be a viable solution. A final drawback is that they use a lot of nuclear fuel… the radioactive uranium is exhausted out the back and lost to space.

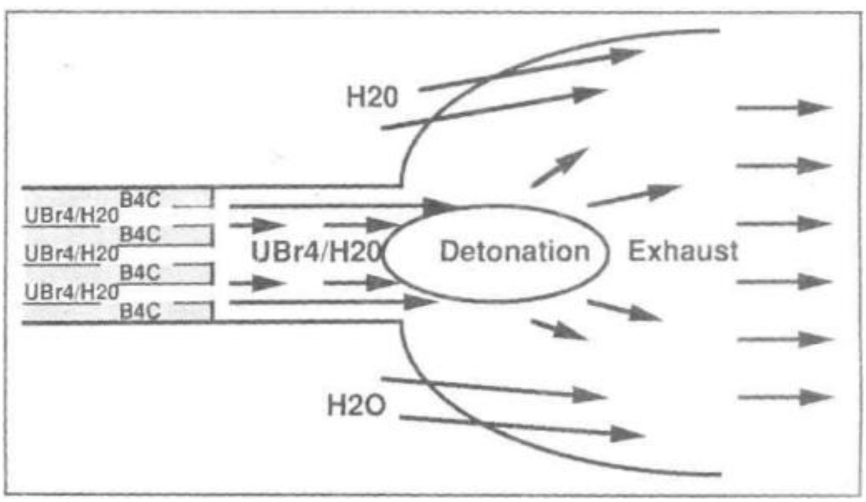


Figure 19-1 Nuclear Saltwater Rocket (Zubrin, Nuclear Salt Water Rockets: High Thrust at 10000 sec ISP, 1991)

The key advantage 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. Trip times within the solar system would be measured in weeks out to Neptune. 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. A Nuclear Saltwater Rocket makes a manned journey to the stars possible (if only barely).

Zubrin himself, while acknowledging the large improvement in performance, points out that even under the best circumstances, a 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, The Case for Nukes, 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.

As far as the next century, I believe we will have and use solid core Nuclear Thermal engines, with slightly improved performance and reliability. Unless interstellar voyages are required, I don't see gaseous, Saltwater or liquid nuclear fission, or Orion style pulse detonation engines as being developed- their radioactive exhaust combines the consumption of prodigious quantities of uranium, make their use case very limited.

Project Orion and Daedalus

There is one and only one technology that exists and could be built now that would allow spacecraft to travel anywhere within our Solar System within weeks and even allow for starship travel. 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

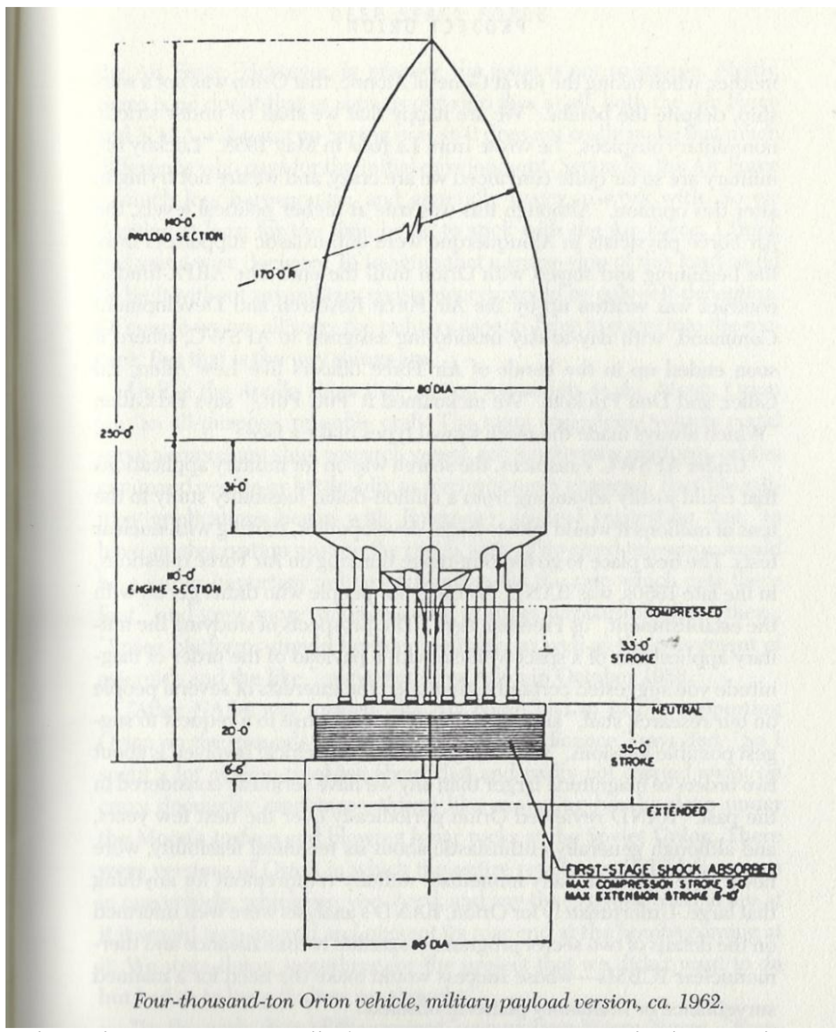


Figure 19-2 Project Orion (Dyson, 2002)

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 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.

Robotics and AI

Robotics and AI are technologies already well developed but neither has approached critical mass. However, the development of specialized, and more importantly, generalized and mass-produced robots will make much of the infrastructure possible. It will be very difficult to support 10,000 human construction workers to build a large Stanford Torus. However, 10,000 mass produced and tireless robots can do the job. Mass produced but very capable robots will be required and the key to building most of the large infrastructure for Space Colonization.

Thinking Way Out of the Box

Throughout this book we have 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.

Fusion Rocket

In many ways, the ultimate dream for interplanetary 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- either directly or, alternately, this high energy stream could be used to heat a working fluid to generate more thrust albeit (increase mass flow) though 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). 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. 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 or power method for at least 100 years.

Solar Sailing

Solar Sailing is in many ways the ultimate propulsion system as it requires no fuel. 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 lightweight and thin materials (ideally on a few tens of atoms thick). There exists the possibility of designing such materials and eventually mass producing them, but if and when this happens remains an unanswered question. This may be an area where zero g manufacturing can provide the environment necessary to manufacture large quantities of valuable materials for export back to earth, though the lack of Carbon on the Moon will push the material sourcing out to Mars or the asteroids.

Solar Sailing, by eliminating the engine and its power source, has tremendous future potential. Indeed, carbon composites, carbon fibers and nano tubes promise revolutionary developments if they ever can be perfected and manufactured in large scales. Besides making solar sailing practical, lightweight and high strength composites make Space Elevators and higher velocity MT engines more practical.

Bottom line is that the advantages of solar sailing, and the lack of theoretical obstacles to implementation means that solar sailing likely will play a large role in space colonization… once the materials are developed.

Antimatter Engines

Antimatter would be the most compact and energetic fuel available. In a perfect world, hydrogen in nuclear fusion converts about .7% of the mass to energy. Uranium nuclear power fission converts about .08%. Antimatter converts 100%. This means that the amount of energy stored per mass of antimatter is about 140x greater than an equivalent amount of hydrogen in a fusion reaction and 1250x greater than the equivalent amount of Uranium in a fission.

There are many engineering challenges associated with building an antimatter rocket. Storage or containment of the antimatter is possible but has never been done on a large scale. However, the biggest problem is creating antimatters in the first place. Antimatter is by far the most expensive material on earth- since 2000 the total amount of antimatter created by the European Organization for Nuclear research has barely created enough antimatter to boil water for a small cup of tea (Los Almos National Laboratory, 2025). Costs are likely billions of dollars per gram. While there remains tremendous room for technological improvement, creating cheap and abundant antimatter will likely be centuries in the future. And once the infrastructure is developed and built to create and store the antimatter, the creation of antimatter will always be at efficiencies of less than 1%, and this is thousands of times improvement over current technologies.

The important consideration is that antimatter is terrible as a source of power. There is no antimatter in our solar system except that which is created by humans. Antimatter is best thought of as a battery, one that may costs hundreds of times more energy to charge than what it saves. Its primary advantage is that once this energy is saved, it is extremely compact.

If it is determined antimatter is required for certain deep space missions, large solar power plants in orbit around the sun could be built that will create small quantities of antimatter over years or decades. Antimatter would make the most sense for interstellar missions that require extremely large speeds- on the order of several thousand kps. The performance of a spacecraft with several kg of antimatter would be impressive and make available interstellar travel- and travel times to the Kuiper belt objects measured in days or weeks.

Genetic Engineering

Humans have several weakness that make the space environment challenging. Baring fundamental changes that would make humans not human (for example, able to live in a vacuum) there are only a couple of areas that are likely to aid in the conquest of space. Increasing our radiation tolerances, increasing our lifespan in general, and perhaps, increasing our ability to live in low gravity. In addition to these items, it may also be beneficial to modify humans to be more susceptible to Suspended Animation (hibernation)(see below).

Suspended Animation

This was a quick survey of all the options available to build a very large human presence in space. The sheer magnitude of major terraforming and world building makes these the least likely option and if done, it will be far in the future. Based on material and power requirements building large space stations will be far and away the easiest and most efficient means of housing millions of personnel. Most resources for earth orbiting space stations will come from the moon. However, for those stations built further out, it is likely that the asteroids will provide most if not all of the needed raw materials.

Less obvious is that terraforming, despite many disadvantages and tremendous difficulties, is likely still to occur. Since most resources for large space station construction will come from either planets or moons a sizeable human presence will be required. These moons and planets are much smaller than the earth, but the large exploitation of their resources will tend to inject many millions of tons of volatiles into their atmosphere, mostly through rocket exhaust, but also through industrial processes like smelting. However, the difficulties of terraforming the moon are in some ways the most challenging. The moon lacks virtually all volatiles (especially Nitrogen) and water- requiring staggering logistics challenges. Furthermore, the moon with its low gravity, requires much more gases than would elsewise be required if its gravity were more earthlike. A steel roof will reduce the importation of volatiles by about 75% but will do little to reduce the water requirement. Furthermore, without a steel roof, satellites and spacecraft will not be able to orbit and volatiles will likely be fairly quickly.

Technology Review, Potential and Maturity

Throughout this book we have looked at a variety of technologies, some already in use, some that could be in use with some further research, and some more speculative. The following list of the technologies we have looked at, the status of their design, and their future potential as related to Space Colonization.

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".

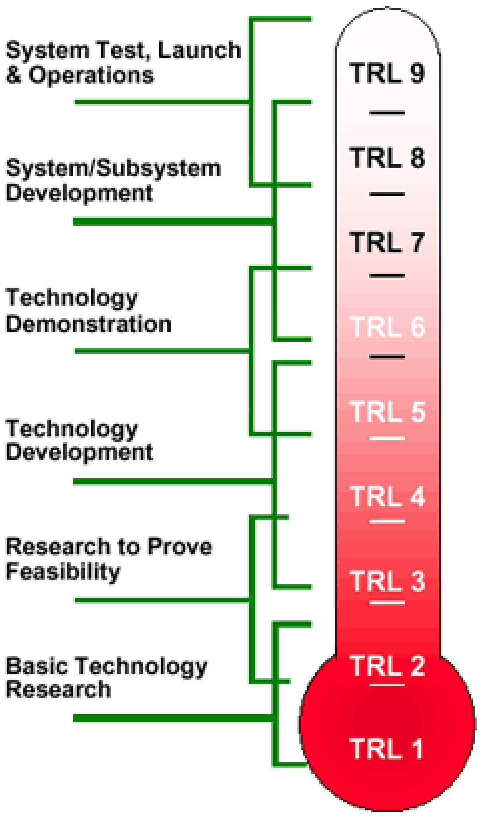


Figure 19-3 NASA Technology Readiness Levels (Courtesy NASA)

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 exits. 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.

Summary and Conclusions

There are many technologies that can be incrementally developed that will make Space Colonization and Development more practical in areas of Power Generation, Propulsion and Miscellaneous Key Technologies. Some of these technologies already exist and are mature on earth and require only modifications to make them suitable for space. Others, while demonstrated on Earth will require considerable development to turn into a viable product for space usage.

Power	Status	Potential Improvements	Criticality toward an interplanetary civilization
RTGs	In Use	Longer Lasting and slight efficiency improvements.	Minor Applications. Insufficient power, scarcity of Plutonium and low conversion efficiencies make impractical for large space stations or interplanetary missions. Suitable for low power, long duration applications like beacons.
Stirling Generators	Tested/Prototyped- Tested but not flown	Efficiency improvements; reliability improvements	Minor applications. Insufficient power supply for large space stations or interplanetary 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 21st 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. In particular, fusion reactors that does not need the relatively rare He3.
Propulsion			
Chemical	In Use		Fully mature. Slight incremental improvement in efficiencies, reliability, manufacturability
Electric Thrusters/Ion Thrusters	In Use	Greater Thrust, mass flow and power handling. Alternative materials propulsion.	Efficiency improvements. Increased power handling and thrust, Reliability and durability improvements.
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.
Momentum Transfer	In development	Earth launch systems are in development. However more advance composites needed to increase dV above 5dv.	Currently can be made for up to 5kps. Need materials advancement to increase to higher increase. Engineering is known and devices are relatively simple.
Solar Sail	In development- Well known technologically but never built on large scale or with high performance (extremely light) materials.	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, however consumes a lot of Uranium
Orion and Daedalus Pulse Nuclear Rockets	Potential development	Technologically sound.	Political concerns, regulatory and material concerns make this impractical. Some versions can be Fusion pulse powered.
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.
Antimatter Rocket	Highly Speculative	Develop more efficient ways of generating antimatter. Develop better containment methods.	Suitable but of unproven and questionable advantages. May never be practical. Takes 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 19-1

Chapter 20 - Colonization- Pro's and Con's

As Thomas Sowell has famously commented-

"There are no solutions. There are only trade-offs."

Space colonization WILL divert resources that can be spent on other things, but Space colonization can lead to materially improvements to human society- including possibly ensuring human survival. In this chapter we will attempt at a high level the trade off, costs and benefits of space colonization.

Should we Colonize Space?

Interestingly, a quick review of some philosophical papers indicates almost universal opposition to widespread space colonization or terraforming of planets. Ian Stoner looks at the ethics of terraforming Mars and concludes that it would not be ethical (Stoner, 2017). In his paper he looks at eight other papers that address similar topics and all are universally opposed to large scale modification or colonization in the Solar System. Mr. Stoner primarily argues against the colonization of Mars by using the Principles of Scientific Conservation. This principle as stated by him says "and principle-violating investigation is impermissible unless the principle of Scientific Conservations is outweighed by a countervailing and more important, moral value." This statement taken by itself is riddled with fuzziness. By this criterion, the invention of fire should not have occurred- there is no way a pre-stone age philosopher could have justified its existence. Similarly, the development of agriculture would have been prevented. Nietzsche pointed out the hypocrisy of philosophers who discounted God but simultaneously came to the same moral conclusions. Many atheistic philosophers assign moral and intrinsic value to inanimate material objects (Mother Earth, the Moon, mountains) not realizing that without god then ALL value are created by humans. Suffice to say that there are powerful intellectual currents in society that are against the development of space, in favor of developing an earthbound Arcadia. These philosophers consistently come to conclusions that are wrong… using their logic, more advanced countries should be more polluting (not true), a more populated planet should be poorer (not true), natural resources are limited and will be exhausted soon (on a practical basis demonstrated false daily) along with other dubious claims. In order to address the issues and concerns involved, as well as arguments for and against Colonization, this Chapter will elaborate on many of the issues. This book will not offer an in-depth refutation of why colonizing space is necessary but for anyone who is interested in the topic, it will bring awareness that many people doubt the moral and intrinsic value of Colonization and will frequently lobby against it. While this book will primarily identify the technical, economic and engineering issues of Colonization, the reader should also be aware that many people regard this endeavor as immoral which adds another dimension to the challenge. The conquest of space will NOT be easy, safe or modest- or unopposed.

As pointed out in the 1970's there was a large intellectual movement that emphasized impending resource shortages. Space was looked at as a possible source for energy, excess population and perhaps a source of raw materials that could indefinitely postpone the pending collapse. However, in the last fifty years, and contrary to expectations, population growth in most of the world has slowed down, and in many countries, started to decrease. Basic economics have played a part in avoiding the worst of the resource shortages by driving increased recycling and improved technologies for extraction. For these reasons I don't believe space will be a major source of raw materials on earth (with perhaps a few exceptions like microwaved transmitted solar power and He3 mining to be discussed later). Space has virtually unlimited resources, however, so does the Earth, and Earth resources are frequently much easier to access. Resources (with few exceptions) are always limited by the effort (i.e. cost) required to extract it. Nonrenewable resources are few in number- most materials can be endlessly recycled. The biggest exception is fossil fuels which when burned break down and become carbon dioxide- though even this is technically renewable if you use enough energy to reassemble the CO_2 to fuel (essentially this is what bio-fuels like Ethanol and bio-diesel are). If a resource is too difficult to obtain, then substitute materials are used, or alternate technologies are developed to aid in recovering these resources. As with fracking, new technology frequently lower the price to extract while increasing the supply of even those items regarded as non-renewable. The only mineral resource on earth and within the solar system that are from a practical point, essentially non-renewable are the relatively rare radioactive elements, like Uranium and Thorium, which are both finite and naturally decreasing as they decay into non-radioactive products. However, even these are likely available in sufficient quantities to support a civilization for tens of millions of years.

One other exception of a rare resource on earth which may be of value in the future is He3. The one element available in space that may be useful for future fusion reactors is He3. In general, there is no primordial Helium on Earth- our gravity is too low to retain this gas. However, minute amounts are continuously created by radioactive decay and some of this gets stuck below the Earth's surface in impermeable layers. Natural gas is frequently trapped in similar pockets and helium is usually found mixed in with the gas. He3 is a very rare isotope of this relatively rare gas and as such is almost non-existent on earth. However, there are other places in the solar system that may have He3 in greater quantities, and we will discuss this in Chapter 4.

By almost any measure energy is the most important resource and is required to access all other elements. Energy makes possible the ability to mine more difficult areas of the planet and to be able to extract and refine the target element(s). Energy is required to separate and recycle material. Once energy is used, it is essentially lost forever. Fortunately, even though energy is the one element that is non-renewable it is available in prodigious quantities, primarily from the sun, and is essentially free for the taking. Harnessing this energy is the engineering challenge and will be discussed in multiple chapters.

If space is not a large source of resources, why should we conquer it? The short answer is we have no choice if we want to survive as a species. The earth has had multiple periods in its history where natural disasters have eliminated most, especially higher, life forms. This will happen again, whether from a meteor strike, large volcanic eruptions, or other more subtle forms of extinction. It is currently known that in perhaps as few as ten's of millions of years (though perhaps as much as a billion), all current life will become extinct because CO_2 levels in the atmosphere will get too low. Despite what may appear as obvious, trees (and plants) do not get a majority of their mass from the ground through their roots, but from the atmosphere- most of a tree or plant's mass is carbon and oxygen which has been taken from the CO_2 in the air around it. Life has been on the earth for perhaps 3.5 billion years and during this time CO_2 has gradually been reduced- over time it gets removed from the atmosphere through a variety of mechanisms and buried in the crust of the earth. In addition, within a billion years, the oceans may start to boil as a gradually brightening sun increases its radiation and the warming atmosphere begins a runaway greenhouse effect. From the perspective of life, the earth is already old and is likely about 80% of the way through the period where life can exist.

Meteor strikes, large volcanic eruptions, nearby supernova, all have potentially severe species level ramifications, and all have occurred in the past and will again in the future. All this assumes we don't accidentally kill ourselves first. It has been observed that intelligence is not necessarily a survival skill. High technology comes with unknown risk. In our quest to eliminate disease, extend life, or improve ourselves, we may, unfortunately, release something that kills us. It is likely that COVID came about accidentally in our attempt to understand and control disease. COVID has a relatively low mortality rate and still devastated the world economy and trade. What would have happened if a disease ten or twenty times more deadly were accidentally or intentionally released? Artificial intelligence and its future relationship with humans are another technology with unknown risk. Nuclear weapons also remain a danger- though perhaps management of this risk is better understood than others as we have lived with this threat for over 75 years.

These are risks we can imagine, but there may be others we have not thought of. Who would have predicted fifty years ago that all the most advanced and developed nations would be voluntarily depopulating? The more "advanced" a country is, the lower its reproduction rate becomes- to the point that it quickly drops below replacement. The reduction of fertility seems to be tied to several seemingly positive trends including increased education and increased wealth, as well as the attendant cultural changes. In advanced societies, careers become more important than family and there are clear signs that educated people believe that humans are a burden on the planet and population must be restricted. The interesting part is that these ideas are widely accepted by large percentages of the population and as opposed to China's since discontinued "One Child Policy", little or no coercion is involved. Society is voluntarily destroying itself.

Related to these trends is the almost religious like social phenomena with the odd characteristic that many wealthy people believe in not reproducing, almost as an atonement. Thousands of books and movies have been written about the future, but few authors recognized or predicted this trend. We have had hundreds if not thousands of books about humanity being eliminated or substantially reduced via Nuclear War, Biological Plagues, War and intolerance in general, alien invasion, AI overthrow, meteor impacts, social anarchy etc. However, the only book that I can think of that captured the essence of the modern zeitgeist was the 1970's book "The Bridge" by Mano D Keith. In it the author envisioned a near future of self-hating humans who would voluntarily commit suicide to atone for being human!

Space colonization will not eliminate any of these risks but a robust multiplanetary species, with different values and cultural norms, will tremendously improve the chance of humans surviving into the next millennia. The diaspora of humanity across planets, and on space stations, moons and asteroids truly will become our defining legacy.

Colonization and Its Enemies

Public support for Colonization will depend on only two things- the perceived cost vs the perceived benefits. For a variety of reasons, tangible benefits are almost non-existent. The primary reason for supporting colonization is the abstract "for human survival".

Absent a strong demonstratable benefit, public support will remain lukewarm. Costs can be summarized as:

- Economic impacts caused by the diversion of resources to space colonization
- Environmental Impacts to Earth

To determine these impacts, we need to first determine what these costs and environmental impacts are?

Space Colonization and Societal Support

A couple of years ago I was investigating the practicality of building an interstellar starship this century (short answer- not very!) I did some research on justifying why interstellar travel (and space colonization in general) is desirable. However, in my research I encountered many, indeed most, academic papers that seemed to be against aggressive colonization. Some of these concerns were practical (environmental costs, economic costs, risks) but most were more philosophical, mystical and abstract. There are many ethical and legal questions about the exploration and colonization of space to include hazards associated with orbital debris, property rights, legal status of colonies, enforcement etc. This chapter will concentrate on the issues and concerns with colonization, though many of the issues and concerns will be applicable to other parts of space programs including exploration and national security.

Since many people reading this book as well as pro-space organizations like NSS and Mars society support exploration and colonization and are already advocates of Space Colonization they do not need to be persuaded. I will not spend much time justifying colonization except in summary. They are:

- Learning
  - Astronomy
  - Geology
- Lure of adventure
- Challenges
- Resource exploitation
- Colonizing for human survival
  - Tangible risks- asteroid impact (we know it will eventually happen)
  - Intangibles- plague, war
- Colonizing for cultural survival

A pew research survey in 2023 indicated general acceptance and expectation for human presence in space, but with some interesting results. In particular, Americans felt that intelligent life being found on another planet has a higher probability than people will build colonies on other planets by 2073. This would strike many as a disturbing result, untethered from reality- but probably reflects the oversold promise from popular movies and books. In another part of this survey, when asked for their priorities for NASA, support for the larger "real" efforts like exploration of the moon or mars, were ranked fairly low, with over 40% of the people saying that sending humans to the Moon or Mars for exploration is not too important or should not be done. This indicates that most

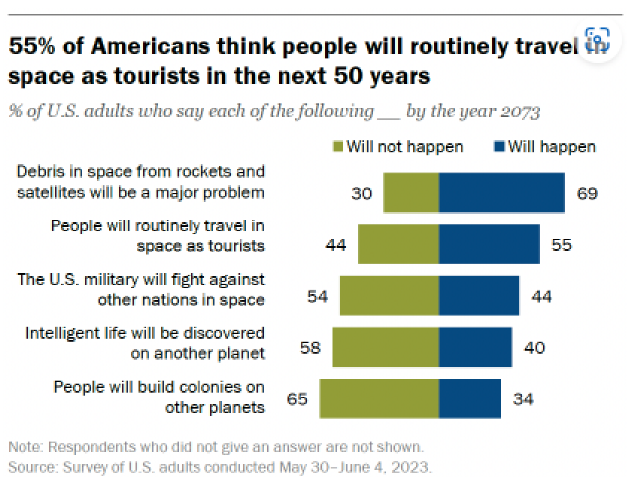


Figure 20-1

people, while not necessarily hostile, will not support large government resources on large scale programs. This also partly explains the continuous failure of large government led initiatives to return to the moon or crewed voyage to Mars. Repeatedly NASA and/or various administrations have attempted to jump start a Mars or return to Moon initiative, only to see these hope wither on the vine.

Short of a major compelling and urgent need to go to these or any other planets, these programs will never get broad public support. Much of society has only a dim awareness of space exploration and colonization, and frequently very inaccurate depictions of it reality. They may support it in the abstract but their support is not very deep. In addition, large endeavors, especially those that involve large construction and infrastructure projects and large expenditure of money in material and economic resources, as well as environmental impacts, concerns quickly come up and support fades.

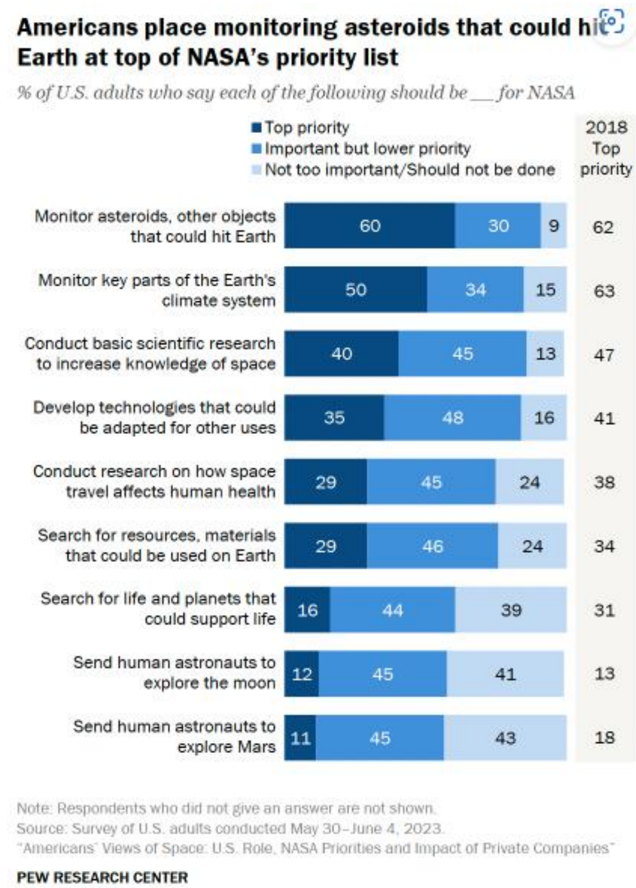


Figure 20-2

Societal Concerns

Below is a summary of concerns. In my nonscientific review of fifteen papers, all were against colonization. Their reasons for opposition varied in some areas but was remarkably uniform in others. After reviewing these papers, as well as articles and postings on line, I listed them, including items which are quantifiable and rational, and others which are philosophical and abstract, with some being both.

- **Environmental**
  - Degradation of the environment (quantifiable)
    - Earth launches and near-earth space
      - Space Orbital Debris
      - Sonic Booms from landing boosters and returning spacecraft
      - Pollution- primarily from launch vehicles
    - Space
      - Debris in space and on the surface of planetary bodies
  - Arcadia- disrupting paradise (philosophical, mystic or religious)
    - Intrinsic Value
    - Marxism
    - Religious

        - Aesthetics
- **Regulatory, Desire for Control**
    - Bureaucratic Globalism/Imperialism
        - Desire to manage or control everything
        - Centralized management required for accountability
    - Fear of technology on Earth and in space
        - Advanced nuclear power
        - Other advanced technologies- biological, mega structures
    - Fear of "others" controlling resources or access
    - Accidents on earth and space related to space colonization
        - Rocket launch incidents
    - Other safety issues
        - Unknown organisms brought back to earth
        - Unknown unknowns
- **Economic-**Some people argue that space colonization will require large expenses that can be better used addressing Earth Issues
    - Consumption of resources
        - Diversion of earth industrial and material resources
        - Malthusian and Marxist perspective
        - Consumption of Space Resources
- **Cultural Marxism/Religion**
    - Fear of missing out- FOMO
    - If everyone can't participate, no one can; Envy
    - Regulation over irresponsible and unregulated "markets" or private individuals
    - Exploitation of resources, prime space
    - Myths- intrinsic value
    - Ownership

I do not believe alien intelligent life will be encountered anytime in the next century, and certainly not within our Solar System. Encountering intelligent life would be a major game changer and would involve in many cases totally different considerations and responses. With that stipulation, I will briefly address each concern.

Concerns- Environmental

The biggest item that the general public will see during the colonization or space is the large launch infrastructure (Spaceports) and frequent rocket flights which will be very loud and hard to ignore. A spaceport, like any manmade structure, will impact the environment. What will those impacts be?

- Atmospheric pollution caused by a high launch cadence
- Noise pollution caused by rocket launch and sonic booms on rocket and booster return
- Large infrastructure including large amounts of land and resources to build the launch port. Substantial logistics will be required for colonization; this includes need for pipelines, large tank farms and launch facilities, large supplies of Methane, and large power requirements. Airports

typically cover many square miles. The Denver International Airport is over 33500 acres or almost 136 square kilometers. Most major airports are over 40 square kilometers. Spaceports may be of a similar scale

- Space Orbital debris- damaged, dead or destroyed satellites or spacecraft that collide with other satellites/spacecraft
- Lunar, Martian and other space contamination

Atmospheric pollution caused by a high launch cadence

Rockets burn a lot of propellant. Fortunately, the most common fuels used (Hydrogen or Methane), used for SpaceX Starship, Blue Origins New Glenn and ULAs Vulcan are clean burning… their engines are primarily Methane/oxygen (Methalox) and primarily produce CO2. Some rockets also use Hydrogen/oxygen (Hydrolox) fueled rocket engines (2nd stage of New Glenn Vulcan, as well as the Aries for the first and second stage) that produce water as the exhaust. Both of these exhaust products are greenhouse gases. Some smaller rockets use refined kerosene or solid rocket engines that are far dirtier and more polluting, but over 95% of the payload to orbit today is carried by a Methalox rocket.

Noise pollution caused by rocket launch and sonic booms (mainly on rocket return)

Besides the exhaust of launch, every day will see the return of a booster and starship and their attendant sonic booms… or 24 sonic booms per day for our notional spaceport. One analysis of the sonic boom caused by the return of the Starship booster indicated that the sonic boom was 50% louder at 20km away than that from the Concord flying at 18km (105db) (Gee, et al., 2024). For this reason alone, it is likely that any spaceport will have at least a 10km buffer around the launch and landing sites that are essentially undeveloped, and another zone 10-25km which has development restricted to industrial purposes to prevent impacts to residential neighborhoods.

One partial solution to the sonic boom issue is to recover boosters and returning spacecraft at sea, where the impacts to civilians would be little to non-existant. However sea recovery adds cost, slows down turn around time, and can damage equipment- salt in particular is pretty damaging to delicate spacecraft. Launching from the ocean can also be feasible, but most of the newest spacecraft are far to large for sea launch and the same concerns on booster and spacecraft recovery exist.

A final technique that could minimize local environmental concern on launch is airdrop- where a large carrier aircraft brings the launch vehicle out to sea where it is airdropped and launched. This is more suitable for smaller launch ships (total airdrop rocket mass would probably only be 150mt) and the same issues with increasing costs and complexity mean this will likely be a niche solution for smaller rockets.

Arcadia and other Religions

Arcadia is a real and dangerous idea that constantly rears its head when humans are making changes to the environment. This fear is frequently quasi-religious in nature and therefore not usually susceptible to rational arguments. Sometimes it appears to be tied up to the seemingly innate idea of original sin in that nature is pure and good, and humans are despoiling it. There are several ways of looking at Arcadia but I will define it as:

- The natural world is pure and perfect and greater than the human world
- Because of this the natural world has intrinsic value, often higher than petty human desires
- Human interference destroys or cheapens this intrinsic value

The environmental movement imposes mythic qualities on the natural world whether it is a tree or a mountain. While it is true that these have value, the value they bring is to humans, the world does not make a judgement or assign a value. An asteroid can and has in the past unfeelingly destroyed this in the past.

In several papers XXXXXXXXX the authors casually made the statements that there is intrinsic value to alien life. Even Carl Sagan made the comment that if microbes are found on Mars we should not colonize- leave Mars for the Martians. This is bizarre as it was a statement from a respected scientist who was also an atheist. The question is why would we leave it for the Martians? Is some divine plan for Martian microbes? Does Martian life have some intrinsic higher value on Mars than Earth life brought to Mars? Does Martian life have some specific evolutionary plan that humans can mess up?

I have respect for these arguments if made by a person for religious reasons but find it impossible to reconcile for people who are atheists and say science should be respected.

Certainly we need to consider the impacts to other life forms if they are encountered, but it should be purely rational. Is the life form dangerous? Can the life form be useful? Answers should be clear cut- and if not, we should proceed with our development. To assume that perhaps one day these items can be useful does not have a history of success, but excessive hesitation leads to interminable navel gazing. The exception of course is if humans encounter intelligent life- here we will need to consider our actions more deliberately.

Concerns- Regulatory, Desire for Control

It is an unfortunate characteristic of human nature that we have opinions and like to tell other people what to do. To some extent this is understandable- their actions might impact us. In the case of space the primary fear would be that "they are doing something we have not approved and may not even be aware of".

However, I already stated that once colonies are established their interactions with Earth will be fairly minor. The colonies will mainly deal with other colonies. There will be tourism but as has been made clear, it will be a small fraction of what the tourist industry handles currently. In the US alone the Tourism industry represents about $2.6 Trillion in 2025 (The Global Statistics, 2025). As discussed earlier in Chapter 18 I estimated that the Mars Colonization effort would need about 3250 launches per year. If we assume an equivalent for a Lunar Colony and construction of LEO and L4/L5 space stations along with the ancillary tourism, it is probably a safe to say in about 25 years we could see up to 10,000 launches a year worldwide. This would be a huge but assuming our launch costs are $100kg and each launch lifts 100mt to orbit, each launch would cost only $10million. This equates to about $100 billion per year for 10,000 launches worldwide- sizeable but less than 4% of the current US travel industry.

Regulatory oversite is definitely warranted to oversee rocket launches as people leaving the earth as well as the local environment could be impacted in the event of a crash or explosion. In addition, certain amounts of regulations and oversite will be required for LEO space stations and Lunar colony visits. Furthermore, earth surveillance as well as any SPSP solutions (including an Occulus) will need to be regulated by the Earth. These would be funded from Earth, launched from Earth, and support Earth with information and power so oversite of these areas would be an area of legitimate regulations.

However, for further colonization (Mars, Asteroids and beyond) regulatory oversite will probably need to be shifted to a regulatory body that is based in space (see Chapter 22). For mining on the moon, Mars, or the asteroids Earth should have little say. These again will be managed by the colonists (Chapter 22).

Concerns- Economics

Broader society has to provide some level of support for humans to become multiplanetary. However, once established as stand-alone, self-supporting colonies, Earth support will be minimal. Earth's primary interaction with colonies and the large space stations will be leisure travel, a source of immigration and perhaps the support of large solar power plants beaming energy down to the Earth. Interaction between Earth and the colonies will only be for the mutual benefit.

The reality is that there are only a few self-paying programs that this new space industry will create- primarily tourism and power supply. Tourism will be a new industry that will help fund the development of some space stations and perhaps lunar colonies. This industry will be new but assuming a few thousand launches per year dedicated to tourism, the economics spent will be fairly small. However it will offer the advantages that tourism to any exotic location offers- expand human experience. Assuming 2500 tourist dedicated launches per year, with 200 passengers per launch, 500,000 people could travel to space per year. The advantages to this is that this money will have created a new industry and helped pay for engineering and scientific progress with materials research, power, electronics and fabrication technology to name just a few.

In Chapter 6 we looked at the economics of SBSP. It appears, that with certain assumptions including launch costs of $100kg, space power beamed to earth could be economically competitive and environmentally friendly. SBSP is already being looked at to provide power to orbital data centers. Data Centers require vast amounts of power- moving these to space will eliminate the power they currently consume, while also eliminating the need to beam down large amounts of power to the ground.

At one time, most people (myself included) would have assumed that governments would take the lead in developing space colonies, but over the last fifty years it has become obvious that governments are extremely inefficient at developing large visionary projects because they are primarily in the business of employment and keeping things stable, and not in the business of development or trying new things. They are administered by and for the "professional managerial class" which leads to the tendency for process to drive the organization and security and stability to be the goal. This leads to a lack of individual accountability but greater concern with narrative rather than taking risk and being agents of change. The recognition that governments are fundamentally incapable of leading in colonization efforts has fortunately allowed private corporations and individuals to take the lead. Because of this, the financial resources required of the government will be minimized and the primary support the government can provide is a regulatory environment that does not unduly burden the private sector. To borrow the often-used phrase of Lead, Follow or Get out of the Way, the primary function of government now is to Get Out of the Way. Because of this, actual government support is surprisingly small.

- Economic support is helpful in several areas
  - Research and development (in particular advancing nuclear power plant and nuclear engine technology)

    - Tax breaks for development of space ports, manufacturing
  - Regulatory support for
    - Development of Spaceports
    - Environmental rules to permit frequent space launches
      - Environmental emissions
      - Noise
      - Permits for development or expansion of space infrastructure
    - A risk tolerant approach to development of new launch technologies

A fair amount of pushback toward space colonization is from a variation on the Malthusian zero sum argument that resources spent on one thing are taking away from another. Historically this has been proven wrong time and again. Many projects have cost tremendous amounts of money but produce little because the incentives were to spend money but not to actually produce anything. Hence over $75 billion has been spent on the Artemis program and essentially nothing has come out of it. Similarly, California has spent $22 billion on a rail system and nothing has been finished after over a decade of work. In California over the last five years, they spent $24 billion on homeless and the homeless problem got worse (Ohanian, 2024)!

In 2019, the United States spent $15,500 per full-time-equivalent (FTE) student on elementary and secondary education, which was 38 percent higher than the average of Organization for Economic Cooperation and Development (OECD) member countries of $11,300 (in constant 2021 U.S. dollars). At the postsecondary level, the United States spent $37,400 per FTE student, which was more than double the average of OECD countries ($18,400; in constant 2021 U.S. dollars). Meanwhile the US education system ranked #17 based on standardized test scores. The conclusion from statistics like this is:

  - Resources, even for worth causes are wasted on large scale

In summary, far higher sums are wasted by federal, state and local governments already with NOTHING to show for it. To keep space colonization going forward with the least expenditure of funds we need to incentivize progress rather than payment, agency over process. Government can help by clearing the way for private individuals and entities to take the lead.

Concerns- Marxism and Religious and Philosophical Concerns

Marxism has never been successfully implemented in the dozens of nations it has been tried in. Indeed most of the largest "manmade" disasters in the 20th century can be attributed to Marxism- including famine caused by Mao during his Great Leap Forward initiative. Among several critical flaws, Marxism never addresses how the market would be replaced. It also envisions a paradise, and is frequently couched in religious terms- the brotherhood of man, workers paradise etc. For this reason, Marxism has many similarities with fundamentalist religions, where absolutes are required, belief is more important than facts, and dissent requires excommunication, or elimination. Rational arguments are discounted for ideology and purity of vision. Marxism is religion without god. For this reason many Marxist concerns are difficult to address- since, as Thomas Sowell has said, "There are no solutions. There are only trade-offs." For fundamentalists, this is untenable. As we already saw with some of the environmental concerns, and in the paradise promised by Arcadia, rational concerns are superseded by religious concerns.With Marxist, one of the core beliefs are Malthusian- that resources are limited and that if you have more than someone else has less. This concept lead to very influential books in the 60's and 70's that stated the world would soon collapse from lack of food, clean water, air etc. This did not happen because Malthusians make some assumptions that are flawed"

- Resources are limited. Technically true, but realistically not. The amount of miniral wealth in the Earth is trillions of times greater than when we have consumed. Space enlarges this pool of resources even further.
- Humans don't change their habits. Time and again we have seen societies adjust their consumption patterns if conditions change. Beef becomes expensive so more chicken is eaten…
- Humans don't invent. Time and again, feared limits are surmounted freeing up additional resources. Fracking is only one such example. Diamonds are another- engineered diamonds are much cheaper and superior in quality to ones mined in the ground. Genetically engineered plants have drastically improved crop outputs and permitted the world to be fed.
- Human nature does not change. While true in some senses, we have seen that with education and wealth, most countries are now BELOW replacement levels

Many of the concerns expressed by Marxism and Environmentalists are similar, with similar thought patterns. Many of the arguments for space colonization will be similar whether the concerns are Marxism, Environmentalism or any other Fundamentalist Religion.

A well-known phenomenon in wealthy civilizations, is NIMBY- or Not In My Back Yard. A wealthy society may like the advantages of an advanced civilization, but the disadvantages associated with many of the advantages are frequently exported far away. The raw materials for electric cars, including the batteries, are almost exclusively mined in Asia or other distant parts of the planet. Solar Panels are almost exclusively manufactured in China. Green nuclear power plants are mostly built and installed overseas. New Green dams and hydroelectric plants are rarely built in developed countries, and sometimes even the opposite occurs- they are dismantled and the dams removed- to help restore the environment back to Arcadia. Plastic waste is frequently exported for recycling or disposal to other continents. Most manufacturing in the developed countries is exported- it still needs to get done but "we don't want it done here". Colleges and education are subsidized, but trade schools are not. Manufacturing is discouraged with regulations and red tape. It is very easy to permit for a warehouse, or office space, but building a factory, oil terminal, or power plant takes years. The list goes on. Wealthy societies support a type of intelligentsia called the "managerial class" of consulting jobs where "recommendations" without responsibility or ownership remove any risk to the consultants. Much of the managerial class has never actually worked in manufacturing and as such are at best, ignorant of these industries and at worst, anti-manufacturing, anti-mining, and anti-construction. Why this occurs is outside the scope of this book but the end result is the same… wealthy societies want the electricity, cars, steel, mineral wealth and manufactured products, but don't want them made in their town. This NIMBYism and the frequent intelligentsia aversion to tangible things means that a colonization program will remain vulnerable to public disapproval.

In keeping with this observation, a quick review of opinions from academia, many publications seem to be against large scale colonization. In general, liberal arts and academia is tolerant of a small amount of exploration but against colonization. The reasons can be broken up into a few major areas.

Unfortunately, the public and intelligentsia are frequently adverse to many of the requirements of a colonization effort.

What colonization Requires:

- Diversion of economic resources
- Large industrial base, including manufacturing and launching facilities
- Long Time Frame
- The physical and mental elite
- Societal and individual grit

None of these appeal to major sectors of the public in the most developed countries, with the possible exception of some places in the United States where the tolerance for risk and development is higher than in European or middle eastern countries.

Space Colonization In Reality

Space colonization, as portrayed in movies, science fiction, and popular magazine articles, is frequently extremely unrealistic. Because of narrative requirements as well as ignorance, many inaccuracies are displayed such as:

- Unrealistic travel times. Except for the moon, and low earth space stations, most voyages will take months
- Unrealistic Gravity portrayals: the only way of providing gravity on a spacecraft is centripetal acceleration (via rotation)
- Unrealistic societal portrayals. Some movies portray space as being homes for the wealthy. Some movies portray a slightly more realistic place filled with blue collar workers. Others portray floating musicians playing or a place for entertainers. While some of this will become true, the reality a colony will be predominately populated with very smart people with families who like to (or will need to) get their hands dirty. It will be a place for mechanics, engineers, and trades. Scientists will not be needed in large numbers- there is little that many scientists can do in space that can't be done better on earth. Exceptions will be for those scientists and engineers who need to perform tasks that may be too dangerous to conduct on earth- primarily those involving nuclear power and genetic engineering.
- After the initial establishment of a colony, families with children will be essential so for self-sufficient colonies so reproduction will be a priority.

On earth, many people with little or no knowledge of the realities of colonization, among them professional managerial class, including colleges and university professors, individuals with liberal arts degrees, etc., will be expressing opinions and, if hired within the government, may be making decisions about how to regulate space. When people with little skin in the game and little knowledge of how a spaceship is made, a power plant is built, or food is grown, are making decisions for others who need pragmatic action, it is a recipe for failure. Decision making must be pushed down to the lowest levels of those involved in the colonization- people with skin in the game. Mao, during the great leap forward, had the desire to help the peasants. His policies lead to the death of up to 60million people from starvation. Well-meaning stupidity and lack of accountability have killed more people over the last hundred and fifty years than all the wars.

The actual conquest of space from the earth will follow the general four stages as outlined below:

- Exploration-Current Stage
  - Ages from 40s-60's
  - Scientists, Engineers
  - Population Smart, Educated
  - Physical fit (top 10%)
  - Mentally stable
  - Small numbers
- Colonization- Next Stage (10-50 years in the future)
  - Ages from 30's-60's
  - Engineers; Specialized Trades; Mechanical Aptitudes
  - Smart, Educated (but necessarily advanced degrees; educated in trades)
  - Physically fit (similar to requirements for the military)
  - Mentally Stable
  - Moderate numbers- thousands
  - Fecund
- Immigration (40years-indeffinite)
  - All ages
  - Variety of skill sets
  - Lower requirements- basic good health and fitness required
  - Mentally stable
  - Ten's of thousands
  - Fecund
- Maturity- Steady State
  - Close to general population

Space travel from Earth will likely always be more difficult than an aircraft flight, primarily because of higher G forces. It is likely that travel to and from the Earth will always subject passengers to g forces that range from 3g to zero g.

In addition, space travelers will occasionally be exposed to relatively high radiation levels meaning that small children and pregnant woman will not be able to travel during certain times. Large colonies will have low radiation levels similar to those experience on earth, but that travel between planets, asteroids and large space stations may not be permitted for this population group. Spacecraft are likely to have various shielding techniques (active and passive) that will bring radiation downs substantially, but still much higher than what is experienced on Earth. Meanwhile, the large space stations and colonies will have more effective shielding and children a pregnant woman can live.

Conclusions- The Reality of Colonization

Space travel will not be available to everyone. There are many reasons for this. Some are technological and may be ameliorated over time, but others are the reality of physics. Some facts about space travel and colonization:

- Space exploration is very hard; colonization is even harder. You are on your own and will not be able to return to earth if your equipment breaks.
- Space colonization will entail large costs and a large amount of resources- but will not be as large as most people expect:
    - Space colonization will likely NOT require large amounts of public funding, nor will it consume a large portion of GDP of the Earth. Some of the space industry will be self-funded, whether by travelers, services provided (such as Earth monitoring and communications (like Starlink)) or power from SBSPP. Once permanent colonies are created, most of the future expansion will be funded by the colonies themselves.
- Governments will primarily be in the role of supporting R&D and setting up a regulatory framework. Private individuals will drive colonization forward.
    - Certain institutions are vastly more efficient than others. It was observed before that SpaceX built the Falcon rocket at a fraction of the cost the government would have spent
    - The conclusion
- Space colonization will have environmental impacts primarily caused by the large number of flights, but the effects, while major, will be far less than the current airline industry.
    - Thousands of annual rocket launches are required just for a Mars colony. For other missions, to the moon or large space stations, thousands more will be required annually. It is not unreasonable to assume that within a few decades 10,000 launches per year will occur worldwide. Space launching will have environmental effects such as:
        - Pollution, greenhouse gas
        - Noise
        - Impacts to the environment
        - Large electricity consumption
    - Emissions from Methane and Hydro lox engines are very clean- primarily emitting greenhouse gases (Methane and Water). The emissions for a colonization drive will be on the order of 15% of the current airline industry.
- Substantial infrastructure will need to be built on earth to support the space industry and colonization.
    - Many more space ports than the current Kennedy/Cape Canaveral, and Brownsville. This high launch cadence will likely support two dozen or more large spaceports, many of which would likely be in other countries.
    - Anticipation that all these space ports will be exposed to dozens of sonic booms per day. This will prevent large space ports from being constructed near large population centers.
    - At sea launch and recovery is feasible but will be expensive. Besides exposing delicate equipment to extreme weather and corrosion issues, large amounts of fuel will need to be transferred to these platforms either with undersea piping or large tankers. Furthermore, if

liquid oxygen will either have to be transferred (also via pipeline or vessel) or large power will need to be supplied and the oxygen can be generated locally.

- Space travel from earth will become mostly one way
    - The initial exploration, construction of space stations, travel to LEO and the moon, and colony set up will involve two-way travel to and from the Earth.
    - As the colonies grow and are established further away (Mars and beyond) return trips will be relatively rare; very few will return once they leave.
    - Tourism will maintain a steady pace but is likely to grow gradually and only to a few thousand flight per year over the next few decades. It will be limited by the items noted in the next bullet:
- Space travel from earth will be elite and restricted, and once in deep space, will be fairly hazardous.
    - Travel from Earth to any point in space will always be expensive. The amount of power alone to send a person into orbit is one to two orders of magnitude more than a cross-country flight. It is unlikely that a journey to LEO will ever cost less than a about 20x that of a commercial cross-country flight, and further journeys will be much more.
    - Space travel will always be more physically demanding than travel on earth. G forces will range from 3-5g to zero g on every flight to and from earth.
    - Space travel to and from earth will always be time consuming, ranging from a few hours to a low earth orbit space station to days for the moon, days to weeks for high orbit space stations and station at the Lagrangian points, and months to years for any of the planets or asteroids.
    - Space travel will expose passengers to high radiation. While large space stations and colonies will have radiation levels similar to earth, rockets carrying people to various destinations will be exposed to high radiation doses during the duration of the flight.
- People on earth will neither have the knowledge of local conditions nor the ability to regulate space once a colony is established
    - Local "residents" will determine the rules (see Chapter 21 for the Regulatory framework).
    - Very simple and straightforward rules will be best. Some regulatory rules that should be in place include:
        - Earth Orbit
            - Satellite removal
            - Abandoned assets
        - Momentum transfer and Mass Driver debris
            - Hyperbolic orbits will ensure that missed payloads depart the solar system.
            - If Hyperbolic orbits are not feasible, launch and recovery rates will need to be established, something like a failure rate of only 1/10000 is acceptable.
        - Buffer zones around colonies and mining operations

Conclusions

MOST OF THE RESOURCES AND PLANNING REQUIRED WILL LIKELY BE FROM PRIVATE ORGANIZATIONS AS PUBLIC KNOWLEDGE AND SUPPORT ARE NOT SUBSTANTIAL

Chapter 21 - Nature of the Space Society

Societies are the product of masses of individuals and how they interact. For better or worse humans have a dual nature- the emotions of apes, including anger, jealousy, joy, love, lust, loyalty and the other, rational side, that is able to control these impulses and use logic and reason. .

Humans also have the following characteristics:

- They don't want to be told what to do
- They want to tell others what to do

The first item constantly reflected in the decisions that societies make. When China became aware of the Western cultures, it did not adopt any of their technologies or make any fundamental societal changes that the West was experimenting with. It was only after multiple violent encounters, first with various European powers, then a brutal occupation by Japan, before it accepted outside ideas. Unfortunately, after a devastating civil war it accepted the worst Western idea ever created- Marxism. This top-down philosophy ultimately led to policies that damaged China and set them back for decades- the so-called great leap forward which led to the starvation of tens of millions and is one of the largest humanitarian catastrophes ever. It was only in the 1980's that policies were loosened to provide for some market forces as well and freer communication internally and externally, that China began to advance. Even now, it is held back by its top down Marxist approach, and its technology consists almost entirely of stolen secrets.

It may seem obvious but to many it is not, but not all cultures will be able to colonize space. The conquest of space will require cultures that are:

- Pragmatic
- Educated
- Hard Working

Pragmatism is perhaps the key- people and society will have to make decisions based on whether the idea works, and not whether it sounds good. The United States partly evolved its pragmatic instincts due to the dangers and challenges it faced throughout its growth. Settlers could not afford to be dreamers… wild animals, weather, indigenous people, as well as threats from various external powers, including England, France, Mexico, Germany, all contributed to a culture that was pragmatic. Space is even more deadly- an untrained and undisciplined person could easily get killed, or worse yet, kill others.

As with Earth, space will quickly evolve into different cultures. Space is vast and in many cases it takes months to travel from one colony to another and because of this different cultural idiosyncrasies will evolve. However, whatever culture evolves, in many ways there will likely be less variation than distance would indicate since the three characteristics listed above will need to be shared.

Interestingly, Space Culture and resources developed in space will NOT be primarily for the use by Earth, just as the creation of the United States was NOT for Europeans, Asians or Africans. Space Culture, like American culture, will be influenced by the cultures of Earth, but will quickly become very independent. At the beginning, when earth provides the necessary technology and resources, earth will have a lot of influence on the colonies. However, as the colonies evolve to self-sufficiency, this leverage will be lost. As between nations on earth, where for economic reasons of efficiency large scale trade occurs, trade will occur between the space colonies but not much trade will occur with the Earth after the first few decades. This is because the Earth already has abundant resources, as well as a logistically mature infrastructure along with its own advanced technologies. Unique manufactured goods that only can be made in low gravity will be exported to earth and depending on what these are, may be substantial. Early on solar power beamed to earth and perhaps He3 will be the primary space export to Earth but few natural resources will be sent back- it is not practical.

I don't see government's taking the lead on space colonization. While discussing the details of why this is so would take its own book, and put us down a rabbit hole, we must at least touch on it as who takes the lead over colonization will both determine the future direction of the colonization, as well as its impact to the earth.

Over the last fifty years the US government, along with all others, has proven uniformly incapable of setting a vision or directing any sort of space colonizing. Many governments on earth are primarily set up for redistribution of resources and pursuing various Marxist influenced redistribution schemes. Most intellectuals are openly hostile to colonizing and the familiar variations of the refrain "with so many problems on earth, we should not be putting resources into space colonization". Again this is a Marxist idea that willfully ignores that very few of the problems the earth has are resource driven, indeed many times throwing money at these problems prevents real solutions from being implemented. Furthermore these sorts of ideas will forever kill any chance of governments taking the lead. In the early 2020's NASAs own website makes no direct mention of colonizing, but instead lists such uninspired priorities as landing a woman and minority on the moon.

For this reason, space colonization will not be primarily driven by governments, but likely private individuals. On Earth, all continents and cultures on earth eventually benefited from the creation of the United States, but the United States was not responsible for the behaviors and cultures of others, and it evolved for itself. Similarly, space will be for the people who colonize it to do with it as they will. Earth will not and should not have much input into how they choose to govern themselves. Only in the case where Space Culture interferes or endangers nations of the Earth, will give and take be required, and nations of the earth may need to exert influence.

Myths about the Colonization of Space

If I had written this book thirty or forty years ago most of my conclusions would have been 180degrees different to that which follows. Based on the intervening years I have drawn some dramatically different conclusions than those of most observer's in the 1970's and 80's. These conclusions are not theoretical but strictly based on observations:

- Space programs are massive but DON'T require multinational or even national resources
    - International programs are driven by ideological reasons or part of a social narrative, but frequently cost far more than a committed smaller team from a single nation or company
        - Costs of the International Space Station as well as other international projects like the fusion ITER project, are so large and unwieldy, and frequently are out of date by the time they are fully developed
        - Multinational efforts must satisfy the lowest common denominator- ensuring that work is spread out (even if this is inefficient) among member states, that all

countries must continuously negotiate and agree to scopes and budgets, have to communicate in different languages, and frequently build or ship needed parts tens' of thousands of miles away for assembly.

- Carrying this down further, large governments frequently are incapable of having either the vision, or the institutional stamina and strength to conquer space. This is further complicated by multinational efforts. Only in the case where there is a perceived threat to a nation's sovereignty, do governments become efficient and motivated enough to produce something quickly. Most government agencies are tasked with ensuring safety, and as a result, find that it is far easier to slow progress down for "safety" than to take a chance on a rapid program that has some risk.
  - Government programs rarely focus on product but on process. They usually are primarily designed for a social agenda and to employee people and in the case of democracy's assisting in the election of politicians. Almost all politicians get elected based on the money spent and not on the end product- the end result is usually unimportant.

- Governments can help to assist with fundamental research into some of the technologies (described in Chapter 14), especially in areas like nuclear power and nuclear engines.
- Governments primarily can assist by clearing the way for exploration and exploitation. Governments can very easily kill any nascent space program with over-regulation and needless caution.
- Not all thought processes and even cultures are compatible with the conquest of space. Indeed, many philosophers and large segments throughout many societies may be actively against it as we saw in Chapter 20.
- The old saw "how can we spend money on space when we have so many problems on earth" is just one of the cultural attitudes that sap national and international efforts. Even today, if not for national pride and not wanting to be left behind, many nations and cultures would be very focused on the past, and would actively push back against newer technologies and ideas. Some of this is for good reason. Some examples of this:
  - Many cultures have rampant theft, weak institutions and legal systems that lack strong property rights and are rife with corruption. Imagine if such a country had nuclear weapons? The chance that they would be stolen, blackmailed or bribed awary, or just lost, are very high.
  - Many "newer" ideas are frequently flawed and can cause damage to a society. Marxism is an ideology that has been very detrimental to the development of strong and stable countries around the world- frequently holding up their economic and political progress for decades. Other ideas, including the widespread depopulation of many countries in the West imply that some "newer" ideas are very antithetical to human progress. Sometimes the old ideas are better.

For these reasons, along with the shear scale of space, all mean that except for LEO, the Moon and the Earth Moon Langragian points, the influence of governments on earth will quickly be reduces to minimal at best- space colonies will choose and prioritize based on their own needs.

So in summary, space colonization and progress will be driven by a few dedicated individuals and their acolytes.

Space Exploration Myths- What Space IS and IS NOT

For at least the next hundred years living in space will be demanding.

Space access will never be cheap.

LEO and deep Space will likely never be cheap to reach. Rockets to LEO need to bring their own oxidizer which has several times greater mass than the fuel itself. Spaceflight, by nature of the need to carry your oxidizer and to accelerate 30x faster than a typical aircraft, will always require much more fuel – currently it is not unusual to consume about a hundred times more fuel/oxidizer per kg carried vs an aircraft, so travel or cargo launched to space will always be far more expensive. As new, reuseable spacecraft are built, this factor should improve but it is likely that spaceflight will always require at least 20x more fuel per passenger than a commercial overseas flight.

Furthermore, aircraft can operate for decades with only minor maintenance after every flight and with several years between major Programmed Maintenance (PMs). Commercial aircraft can easily fly thousands of flights during their lifespan. Reuseable rockets, which have far greater structural and thermodynamic loads will likely have a far shorter lifespan. I foresee a future version of the Starship or its successors that could survive a 100 launches with only a moderate amount of maintenance between launches- with the spacecraft being retired after that. The costs for the design and construction capitalization of each spacecraft will have to be spread out among far fewer flights than an aircraft.

The same goes for the ground infrastructure. A large commercial airport can have hundreds of flights per day and the costs of building and operating this airport can be spread out over all these flights. I do not foresee any spaceport handling more than a few flights per day.

All this means that spaceflight to LEO will always remain relatively expensive- perhaps about 20x more than a typical airline ticket being a reasonable if aggressive target.

Space will not be for the infirm- at least for the first few decades

It has been observed that most Americans cannot pass the fitness requirements to join the military. The situation for space travel is similar. Spaceflight will likely subject passengers to high g loading during take off and landings with a range of between 3-5g.

Spaceflight will also periodically expose people to zero g. People with severe motion sickness may not be able to tolerate this.

Spaceflight will likely expose passengers to elevated radiation for at least portions of their travels. While this may not expose most passengers to unreasonable risk, it will be prudent that susceptible people (pregnant mothers, children) not be exposed to the risk.

Cruise ship passengers, as well as aircraft passengers, have to have safety briefings. Spaceflight travelers will also have to be briefed on emergency procedures. These will be more elaborate, and more physically demanding than cruise and aircraft briefings. People who are physically compromised may not be able to follow safety guidance to include possibly donning and doffing a space suit. Depending on the destination spacesuit wear may be required in emergency situation and it is unlikely that they will be available in all sizes. Children or very small adults, as well as obese or very tall adults may not be able to fit in the suit available. Space emergency lockers or pods may be an alternative to get around these limitations.

To travel and live in space, besides being intrinsically dangerous, will also require training over and above that for airline and cruise ship travelers. Standardized language will be required. Even today, airline pilots all over the world are required to converse in English. Emergency instructions will likely be standardized in a single language.

Because of the dangerous and challenging environment, initial colonists will have to be both intelligent and with a diverse skillset- likely far above the general college population which currently sits at near average IQ of 102.

As with the military, mental health issues will be very dangerous in the space environment and mental health screening for new colonists as well as ongoing mental health monitoring will be required.

Today, many industries and careers (including pilots, truck drivers, pipeline operators) must submit to mandatory and random drug testing. Cigarettes, Marijuana and most if not all recreational drugs will likely never be permitted on spaceships- at least until massive and robust stations are constructed where people live permanently.

Finally, and paradoxically, for long term permanent occupation to occur, children must be born. After the initial construction and development phase, what space colonies will most need is reproductive families.

In summary, spaceflight will likely not be possible for people who are frail (elderly), have heart conditions, are obese, handicapped, sensitive to elevated radiation exposure, claustrophobic, have chemical addictions, are suicidal or violent, or under the care of a psychiatrist and take prescription drugs for mental issues.

In short, this will eliminate nearly 90% of the population. Space travelers, at least in the next half century, will primarily be open to people 20-50, above average in intelligence, physically healthy, within a moderate weight range, with no drug or psychiatric issues and ideally fertile. Over time this pool of eligible people will expand and by default, people born in space will stay there, and they will NOT have these characteristics- they will quickly return to the mean. This will be dealt with as required, but at least for the next half a century or so, restrictive requirements will be in place.

Space will not be a source of Resource or a place to export excess population

Finally, as discussed throughout this book, Space will NOT be a source of Resources for Earth- except perhaps power and very rare elements. The costs of Mining and then shipping back to Earth are just too great. Raw materials are generally abundant on earth and much easier to access than the moon or distant asteroids. The only exception to this is SBSP stations which could provide green energy, Helium 3 resources for fusion power plants, and perhaps high value elements like Uranium as well as specialized manufactured goods that can only be made in space.

Similarly, the costs of launching materials and people into space are too high, so space will never be a reservoir to send excess populations. This will also be the reason hazardous waste will not be shipped off Earth.

The Business Case for Colonization- What Space Can Be Used For

If these items are all the things Space will not be good for- what good is it?

I can see the following revenue generating businesses for the initial colonization of space:

- Power
- Tourism
- Specialized zero gravity manufactured materials
- Minor rare elements (He3, platinum, gold)
- Scientific instrumentation. Large scale telescopes are an example
- Communications

Communications is already a major source of revenue for several companies, including SpaceX, and is likely to grow considerably more over the next couple of decades. Other revenue generating business not shown are earth monitoring (including weather) and satellites used for resource identification. However, while the benefits of improved weather monitoring or resource identification are significant, the actual cost to provide these services is relatively small and the demand is limited. Little would be gained by having thousands of weather satellites when only a few would do.

This business revenue will provide the initial capital for the first few decades of colonization- and will primarily be used for developing a building an efficient and large launch industry. This launch industry will be used to send people into orbit and beyond. Just as importantly the revenue will be used to design and develop the initial hardware for use in colonization (rovers and various vehicles, power plants, furnaces, drilling equipment etc.). However, after the initial small colonies most of the raw materials and the construction of a majority equipment will need to be done by the colonists with only minimal support from earth.

Governments can help by continuing to help with basic research, but more importantly, by creating a regulatory environment that will help entrepreneur's and the space industry to grow. Primarily this means that the launch industry needs to be relatively free to build their launch facilities, and launch their rockets. A supportive regulatory environment is REQUIRED to have a robust launch industry. Excessive regulations will destroy the launch business, and make colonization impossible.

Other than supporting a launch industry, except for supplying the original population in the form of colonizers and then immigrants, Earth will not need to supply much in the way of raw materials for space- it will always cost too much. Even to this day, while air travel is relatively cheap, almost all cargo between nations are transported via ship- which are frequently several orders of magnitude cheaper. Spaceflight, by nature of the need to carry your oxidizer and to accelerate 30x faster than a typical aircraft, will always require much more fuel - usually about a hundred times more per kg carried, so travel or cargo launched to space will always be more expensive than an aircraft.

Technology transfer, initially, will be mostly one way- the Earth will provide. However, it is likely that within a few decades, technology transfer will be both ways. In short, after thee first few decades, most raw materials will be sourced from space. Technology, in the form of hardware and knowledge will migrate from Earth but even this will fade as "locally manufactured" items begin being made.

The Moral Imperative Case for Space Colonization

As discussed in Chapter 20, space colonization can be justified from a purely moral imperative. However, historically this has rarely been done. The colonization of America happened because of the opportunities, political and economic, were a sufficient lure to cross an ocean, leaving family and country behind, to risk danger and uncertainty, all for the abstract chance that life would be better.

One earth today, especially the wealthy countries with the greatest opportunity to engage in space colonization, this is not the case. The worlds richest countries are democracies with frequently laws protecting speech and religious observations. Food is abundant- so much so that the poorest citizens have the highest obesity rates. Desperation will not drive migration.

With that being said, the difficulties in migrating to space, the need to build an interplanetary infrastructure, will severely limit the pool of individuals who can go. Even several decades from now it is unlikely that more than a few tens of thousands of people will leave the Earth for Space. The amount of people who will want to go is much less than when America was colonized. The question is the pool of people who desire to migrate is big enough even to fill the small opportunities that will be there.

My feeling is that the limited Business Case, combined with the Moral imperative- their will be some people and families drawn to the challenge- and that will be enough. Only time will tell.

Regulatory Oversite- Deep Space Development Council (DSDC)

In order to have a successful and thriving space faring civilizations, some common rules will need to be implemented to ensure a future home for humanity. The rules should be simple to understand, simple to implement, simple to monitor, and have widespread acceptance among the colonies and developers.

The Deep Space Development Council (DSDC) are the proposed regulatory and administrative body that regulates mining and colonization. The Initial organization will likely be based on the Earth but will be required to move their offices by 2050 into space. The DSDC will primarily serve the following:

- Vetting and issuing of Colonization and Mining Permits
    - Developing the documentation and tracking of such permits
    - Collection of relevant fees (fees will be very minimal for application)
    - Verification of permit term compliance
    - Mediation and resolution of colonization and mining conflicts
        - All Colonization permits will permit the holder a vote with a $10,000 membership fee
        - An additional vote will be allocated to a specific colony for each 10,000 permanent residents or 1% of space population
- Common Space Infrastructure (CSI) Group
    - Establishment of the Tracking Database Group (TDG)
        - Development, Construction, Deployment, and Operation of:
            - Tracking and Relay Satellites (TRS)
        - Maintenance of the Tracking Database from data provided by the TRS the Permit Group
        - Any additional CSI that the DSDC has approved
- Permit Group
    - DSDC Permit Group will review and provide for approval of all permits. Turnaround time for permits will be 72 hours. If permit is rejected the reason must be stated in detail. Permit approval will be automatic unless members vote to disapprove. Permits, and any

associated fees collected, the permit tracking and compliance oversite will be maintained by the DSDC.
    - All voting members can provide comments or vote to deny a permit. However, all permits require a 72 hour turnaround time. Permits can be rejected only if 60% of voting members agree to reject, otherwise permit approval is automatic. No vote is assumed a positive vote.
- Changes to the charter rules require 90% voting member approval. No changes can be approved until DSDC has been in operation for 15 years.
- Funding will derive from various sources:
    - Permitting
    - Membership in the DSDC. Membership will give access to the TDG database

Space Regulatory Committee (SRC)

Space is vast and resources essentially inexhaustible. With that being said, their needs to be in place some measures/rules that will ensure its accessibility and safety for centuries to come. Because natural space is already toxic and deadly, the goal of this organization will be to ensure space is not made more toxic or deadly. Fortunately, this is rather easily accomplished by a few rules and an oversite group. The first department under the DSDC will be responsible for developing the rules for space colonization and exploitation. They will develop the Permit forms, as well as develop policies to ensure the safe development of space.

While we can hope that there will never be warfare in space, there needs to be a regulatory body to both develop minimal rules as well as to resolve issues and enforce regulations. I will call this organization the SRC (Space Regulatory Committee). The SRC will be a relatively small organization who will have a dual mandate of Safety and Space Exploitation to include commerce. They will come up with rules and standards. However, due to the various and sometimes conflicting requirements of the future colonies, there rules will have to be very minimal. In keeping with the desired peaceful use of space, as well as the sheer scale of space industrialization and the large number of colonies that may proliferate over the next two hundred years, I don't believe they will have much ability to enforce their decisions, but this would be the responsibility of the Compliance and Enforcement department.

Compliance and Enforcement can work through moral persuasion as well as support of the colonies/settlements that are under their jurisdiction. Tools that may be used are various types of boycotts, or the denying of citizens of one colony from entry to other colonies etc.

The SRC will be a facilitator in resolving issues between independent colonies (Space Stations, Planetary and Lunar colonies etc) if requested. In some ways it will resemble the United Nations, in that they can act as a forum for member colonies to discuss concerns or issues. However, the actual organization will be very small- perhaps a few dozen personnel who would both draft policy, identify enforcement issues, and make decisions and determinations during disputes. In general, they will be wholly dependent on the colonies for enforcement and will primarily serve as an advisory organization.

The SRC will also be responsible for revenue collection. Revenue will be derived from:

- Colonization permits
- Mining Permits
- Voting Membership of the DSDC

- All voting members of DSDC will have access to all TDG and Permits
- All voting members of the DRC will be required to contribute an annual fee of $5000
- Members who do not contribute will not have voting privileges and will have limited access to the TDG

Use of Nuclear Devices

One example where some sort of regulatory agency will be beneficial is with the use of nuclear devices. Use of Nuclear devices may be necessary for terraforming purposes, transportation etc. and should be minimally regulated. However, to ensure a nuclear device does not damage a colony, space station or satellite, some sort of approval authority should be involved. They would need to assess the risk and approve any nuclear detonations. The SRC will be that agency, though, as mentioned, they will be strictly advisory.

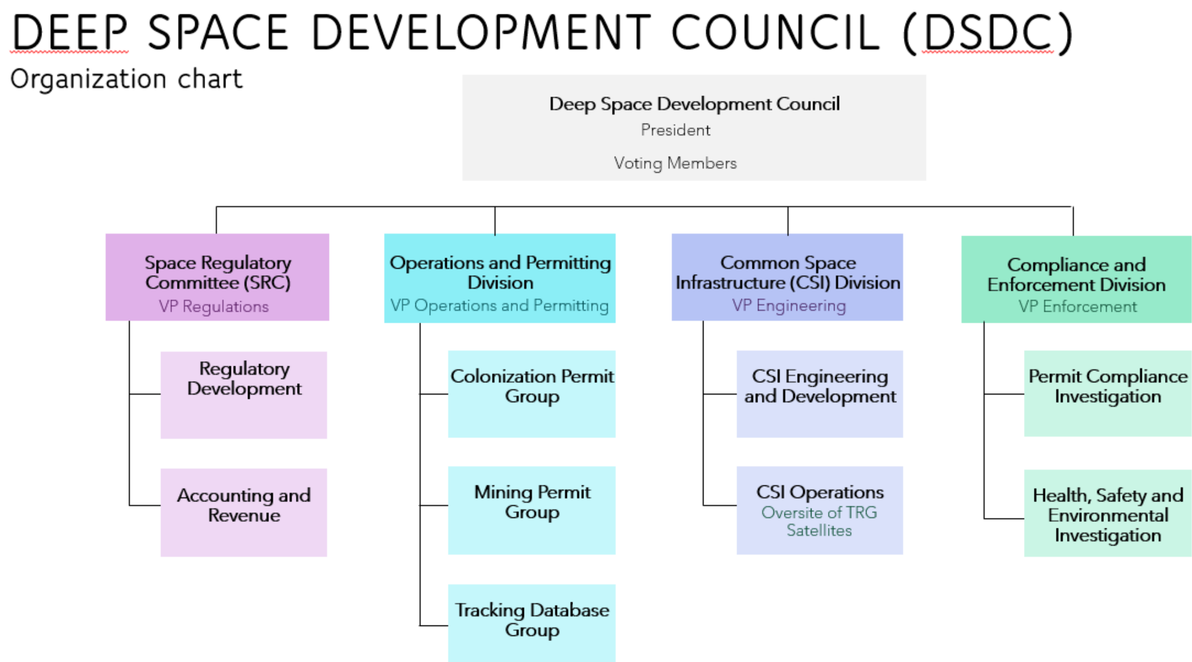


Figure 21-1

Operations and Permitting Division

Permits will be issued to allow for colonization and mining. The Operations and Permitting Division will be responsible for ensuring permits are deconflicted before approval, the permitting and TRDG information is available for all DSDC voting and non-voting members, as well as elevating concerns, conflicts or questions to the Enforcement (or other relevant division).

Colonization Permits Group

- $10,000 fee to submit colonization permit

    - Any nation, corporation, or individual can submit a permit. To facilitate transparency, Corporations and individuals are required to list the names of the individuals (not to exceed 10) that the permits will be issued to.
    - Permits will be dated on day submitted. Operations and Permitting Group will have 72 hours to approve or disapprove with comments. Permit start date will begin the day permit is submitted.
    - Permit will specify what body and the recognized Latitude and Longitude location that will be colonized.
        - For large bodies (ie planets, large moons and minor planets etc) over 10km diameter in size permit will allow for an exclusive 400 km^2 lot (nominally 20kmx20km)
            - Alternative lot sizes will be permitted but will require review. Alternate lot sizes can not exceed 400km total area, can not impinge upon another permitted lot, and must be a minimum of 5 km wide
        - For small bodies Colony Permit will give permission for exclusive colonization and ownership of any minor planet of 10km or less
        - Establishment of a permanent habitation (1+person) is required Five-year after permit approval with the option to ask for a one-time five-year extension at an additional $10,000 due at expiration.
    - Once permanent habitation is established, permit will be in perpetuity as long as colony is occupied. No additional fees will be required after the initial payments
        - In the event of eventual colony abandonment, permit will lapse within five years of abandonment and available for resale by the Operations and Permitting Group

Mining Permits Group

- $10000 fee to submit Permit for Mining
    - Permit will allow for the exploitation and mining of resources within the permit lease area.
    - Permit will specify what body and the recognized Latitude and Longitude location that will be mined.
        - For large bodies (ie planets, large moons and minor planets etc) over 10km diameter in size permit will allow for an exclusive 400 km lot (nominally 20kmx20km)
            - Alternative lot sizes will be permitted but will require review. Alternate lot sizes can not exceed 400km total area, can not impinge upon another permitted lot, and must be a minimum of 5 km wide
        - For small bodies Mining Permit will give exclusive permission for resource extraction of any minor planet of 10km or less
    - Materials extracted will exclusively be that of the permit holder
    - Mining operations to begin within five years of permit, with optional five-year extension for $10,000 additional fee
        - At the end of this five- or ten-year period, if mining has not begun mining claim will revert back to the DSDC

    - If mining operations are active, then permit will be reviewed every five years to ensure operations ongoing
  - Mining operations are considered to be active or ongoing if:
    - 1000kg minimum export per year or
    - 10,000kg export in a five-year period
    - If mining operations cease or the export quantities are not met per the permit, then the mining permit will revert back to the DSDC.
    - Export will consist of extraction and movement of material off the permit area with a minimal transport distance of 100km.
- Any colony planet, moon or minor planet develops a unified governance, (hereafter referred to as "Unified Planetary Government- UPG") that exceeds 1million full time inhabitants will have the option of pulling the permit process out of the DSDC and having the UPG approving permits for their body. The SRC will review and provide regulatory guidance to assist with the transition.

Tracking Database Group (TDG).

The TDG will be funded and operated under the Operations and Permitting Group. It will consist of a small group of people who collect and maintain a database of all known objects in the solar system and beyond. The CSI will be responsible for the construction of a satellite network called the Tracking and Relay Satellites (TRS). The TRS will be the primary, though not only, source of data for the TDG. TRS satellites will be in sun centered orbits positioned at various points in the solar system (see below). The TDG will function as an Air Traffic Control and Coast Guard, collecting data, deconflicting missions, and approving waivers.

The goals of the TDG are:

- Minimize debris in the solar system and around all planetary and lunar bodies by:
  - Any mass driver projectiles must be actively controlled and designed to be retrieved or, if not actively controlled, planned to either impact or proactively tracked to its planned termination point.
  - All non-actively controlled payloads that are not destined to exit the solar system must be approved by the TDG to ensure an adequate recovery or termination plan. Otherwise, all non-controlled payloads must have a hyperbolic velocity and permanently leave the solar system.
  - Any mass (spacecraft) that is manned or is the size of a SSCME or larger must have a transponder or be on a hyperbolic trajectory.
  - Any mass that is manned or the size of an SSCME or larger, or under active control must not come within 100km of any item in the Tracking Database unless
    - It is scheduled to rendezvous with the item.
      - All rendezvous activities must be relayed to the TDG.
  - Any mass that is unmanned and smaller than the size of an SCSCME and is not actively controlled must not come within 100km of any item in the Tracking Database unless:
    - It is scheduled to rendezvous or impact the item.
      - All rendezvous or impact activities must be relayed to the TDG
    - If object(s) are not planned for impact or rendezvous, they must be on hyperbolic trajectories and must still obey the 100km exclusion zone.

        - All planned exceptions must be relayed to the TDG for assessment, comments, and waiver approval
- Any retired, dead or derelict spacecraft must be Safed. The following options are acceptable:
    - Each of the following must be executed:
        - Positioned in gravitationally stable graveyard orbits (L3, L4), or on the surface of an asteroid/comet/moon/planet, or placed in orbits with no known impacts for 10,000 years.
        - Fuels removed; tanks degassed to prevent explosion.
        - Detailed final disposition information provided to TDG.
    - Destroyed in planetary or lunar atmosphere within five years of asset retired/declared dead/derelict
        - Detailed disposition information provided to TDG
    - Placed in hyperbolic orbits that exit the solar system
        - Detailed disposition information provided to TDG
    - Dropped into the sun within five years of asset retired/declared dead/derelict
        - Detailed disposition information provided to TDG
    - Any waivers to the above must be approved by the TDG.

Common Space Infrastructure (CSI)

As civilization spreads, the amount of personnel and cargo will grow rapidly. To ensure safe and efficient operation, a limited but common infrastructure needs to be in place. This will be managed by the CSI Group and will include and engineering Group, which will design, build and maintain a satellite network. See Chapter 11 on Logistics.

Tracking and Relay Satellites (TRS)

The TDG extensive database will be populated by data primarily provided by the TRS. The TRS will be developed, designed, launched and supported by the Common Space Infrastructure (CSI) Division. Characteristics of the TRS Network are:

- Initially there will be three satellites in the Martian L3, L4, and L5 points, later, additional satellites may be established at Jupiter's L3, L4, or L5 positions. They will operate as follows:
    - Passively and actively identify manmade and natural objects and will relay their information to the ground TDG. Similar in design to Gia, they will continuously scan the sky, looking for low light objects- likely down to magnitude 20 or 21. This will pick up both asteroids, comets, Kuiper and Oort cloud objects, as well as manmade objects.
    - They will be fairly large solar powered satellites which combine passive scanning sensors like the Gaia spacecraft, along with accurate atomic clocks and a powerful pulse transmitter to transmit time and location data as with GPS satellites. An advanced version would also pick up the pulses from ships or payloads that have active transmitters- like a transponder on aircraft or RFID devices on packages.
    - These satellites will download position information twice per day to the Tracking Database and Relay Station (I assume that spacecraft will be larger than Gaia and take twice as long to perform one revolution- or 12hours for a single scan of the sky).
    - These satellites will actively pulse transmit once per hour with detailed positioning data- similar to GPS except they will not transmit continuously. This data can be used by nearby spacecraft to determine precise location. Combined with the other two

satellites, extremely accurate positioning information can be determined, however more distant spacecraft may need to have a collecting radio dish to pick up the weak signal from more distant TRS satellites.

  - The data collected will also include parallax information on stars (as with the Gaia spacecraft) but since they orbit more distant from the sun than Gaia, they will have greater accuracy.

- Transponders or Radio Frequency Identification devices will be installed on certain equipment. In addition to the passive capabilities built into the TRS, all manned, as well as all large, unmanned cargo spacecraft should have both a transponder- a device that transmits identification information when queried, and also an active pulse transmitter to highlight the spaceship. This active pulse will likely transmit via radio frequencies, but an optical light may also be developed- similar to a periodic strobe and the lights on aircraft. All manned spacecraft, as well as large unmanned or free-floating containerized spacecraft (PSSCME (Powered Space Standard Cubic Meter Equivalent)) and larger will need a transponder.

Conservation of Resources

As on earth, most resources are recyclable and almost infinite in supply. The primary issue with many resources is that as they are extracted, the most easily accessible resource is tapped first and subsequent resource extraction is more difficult and frequently more damaging to the environment. However, with continuous advances in technology, as well as the application of sufficient energy, the “accessible supply” usually grows faster than it is consumed. The best example of this is with Oil, which has been forecast to run out multiple times over the last century. The technological development of fracking essentially increased the amount of easily accessible oil (at little additional cost) and was so successful that the forecast available oil supply is now greater than it was 100, 50 or even 20 years ago.

For the next few centuries, human impact to solar system resources will likely be negligible. Most bulk resources used should be low value items like lunar regolith for cosmic ray shielding. We see a similar situation like this on earth where the most common material manufactured today is concrete.

Volatiles released to space will be permanently lost. Rocket exhaust will be non-recoverable, whether it is Hydro lox rockets where the hydrogen and oxygen are released as water vapor, or carbon, hydrogen and oxygen from Methalox rockets. Nuclear rockets likely will use hydrogen for fuel which will also be lost. However, in all cases these resources are effectively inexhaustible… the Solar System likely loses many billions of tons per day from atmospheric and surface loses of the various planets, moons, comets and asteroids from impact erosion and solar winds. The sun itself loses about 1.5million tons per second through the solar wind (in addition to another 4million tons of mass lost through fusion).

Some of the noble gases, in particular Argon, Krypton and Xenon may also be lost if used for electrostatic ion propulsion, but, as we saw with Argon, the supply just from the Earth is nearly inexhaustible. Over the next few hundred years, the Earth’s atmosphere will be the primary source for these noble gases. Argon, in particular, is prevalent in the earth’s atmosphere. Xenon is far and away the rarest. It is possible that over thousands of years, some additional sources for Noble gases may be economically developed. Both Venus and Mars have modest amounts of Argon in their atmospheres. Xenon is likely present in the atmospheres of some of the gas giants. However, based on the large Earth Supply it would be best to develop Argon into the preferred fuel for Electric Thrusters.

Volatiles will be shipped across the solar system, whether to provide the atmosphere to large space stations, rocket exhausts, or many orders of magnitude larger terraforming of planets. Nevertheless, the materials most needed would-be Nitrogen, Oxygen, and Water are very abundant and essentially inexhaustible.

The one resource that is very valuable, very rare and is consumed by civilization, is Uranium. Earth likely has the most easily accessible sources of Uranium since it had a geological history that caused some areas of the crust to be enriched. This sort of history is unique to the Earth and because of this, Uranium, while present on the Moon, Mars, Asteroids, is likely very diluted and spread out, making it difficult to exploit.

Thorium will likely be a preferred fuel for most of the future space colonies as it is usually 3-4x more abundant than Uranium and may occasionally be enriched to much higher levels.

Chapter 22 -CONCLUSIONS

Space is vast and hostile, but also fantastically rich in resources including energy. With the technology at hand, large colonies can be built now. What is lacking are the human resources, men and materials, to make this vision a reality. However, it is all there- just waiting for the us.

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 Kilometer^2= 247 Acres

1 Acre= 4047 m^2

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/m^2

1 Watt= 1J/s

Appendix B- 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	841.051	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 0-1 Planet and Dwarf Planet Data Table

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