SPACE MINING AND MANUFACTURING

Off-World Resources and Revolutionary Engineering Techniques

DAVIDE SIVOLELLA

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Contents

Preface

In 2019 we celebrated the 50th anniversary of Apollo 11. What a truly outstanding achievement it was! In less than 70 years, human society saw the first flying machines evolve into spaceships capable of delivering two individuals to the surface of the Moon, possibly the most inhospitable environment to life humans have ever ventured into. Even more remarkable is that Apollo 11 came less than 12 years after Sputnik, the first satellite in space, and less than 9 years after Yuri Gagarin became the first person in space.

The Apollo program was a victim of the particular historical context called the Cold War, in which what mattered most was to show technological superiority rather than a genuine motivation to undertake space exploration for the benefit of humankind. This explains why, fast forward to the present day, none of the grandiose plans of space exploration and development which so animated the 1960s and 1970s came to fruition. For the most part, space activities are dominated by political ideology and scientific curiosity, in particular in the context of human space exploration. A return to the Moon or a mission to the Red Planet are from time to time promoted by all the major space agencies. But until the financial support needed to back such ambitions is forthcoming, nobody is going to start cutting metal. Perhaps, even more demoralizing is the lack of endorsement from the general public. Sending people to the Moon or Mars, or sending robots to photograph alien worlds billions of kilometers from Earth can briefly capture public attention, but many people would gladly get rid of space exploration and divert financial assets and talent into solving the pressing issues affecting our society, notably climate change, environmental pollution, and the scarcity and control of resources.

I have been a life-long advocate for the development of space, but I must admit that since an early age I have always felt a pang of distress at seeing how space exploration seemed so far removed from assisting society in overcoming the predicaments that are increasingly threatening our future on this planet. Out of such dissatisfaction, I started to embrace the notion of moving our manufacturing industries into orbiting factories that draw their resources from the Moon or asteroids. Many studies dating back to the 1970s and 1980s have discussed off-world mining and manufacturing. Today they fall under the banner of "living off the land" and envisage permanent outpost on the Moon or Mars. This is a worthy notion, but it is a restricting way of thinking because there is so much scope for exploiting such research to the benefit of humankind here on Earth. Mining and manufacturing activities can produce waste products of such kinds and in such amounts that they cannot be metabolized and neutralized by the air, water, and soil in the environment. In exceeding the capability of the environment to absorb what we throw at it, we face long-term pollution. Factored across the whole globe, we have now created the conditions for climate change, endangering of animal species, and loss of human lives. Our frantic way of living is also exhausting the resources of the planet. Many conflicts between peoples arise from efforts to exert control over ever dwindling resources.

There is no danger of environmental pollution in space, since there is no biosphere. Water and minerals are available on the Moon and countless mountain-sized asteroids. We have grown familiar with such ideas in science fiction stories, but rest assured it is not beyond of the realm of real engineering. We are already extracting resources in the most inhospitable environments, such as the ocean floors for diamonds and fossil fuels. We have built prodigious infrastructures such as dams that halt the flow of some of the largest rivers in the worlds in order to produce electricity for whole countries. We have built pipelines crossing land and sea to pump fossil fuels between countries thousands of kilometers apart. In open-cast mining we have dug pits so deep there are different microclimates at the top and bottom. Automation is allowing the extraction industry to work mines with completely automated machinery. Whenever there is a need, human ingenuity can achieve great things. The aim of this book is to show that space mining and manufacturing are within our current technological capabilities. If we implement a practical development strategy, such as that described here, we will gain a concrete opportunity to transform such thinking into reality.

Rest assured however, that unlike many fellow space advocates I am not preaching the development of space as a panacea that will enable us to write off environmental degradation, resource scarcity, and the like. Instead, I do believe that it has the potential to contribute to the mix of strategies available for tackling those issues. For the last 60 years of space exploration, we have been guilty of seeing space as a place for discovery and exploration. Now it is time to consider it also as a resource, and set a new space exploration and exploitation path that will genuinely benefit humankind.

I hope you find the material in this book sufficiently informative and convincing that you will join me in advocating to make such a vision a reality.

Acknowledgments

It seems to me that writing a book must be one of the loneliest projects an individual can undertake. It means spending countless hours researching and studying in advance of even drafting anything meaningful. As chapters are developed, they are periodically reviewed, rewritten, amended, or pruned until the quality of the content and narrative fulfill the master plan. It may take years before the manuscript of a 200-page book can be presented to the publisher. In all this time, the author has to spend hours at the desk, reading, note-taking, and typing. Inevitably, this entails subtracting precious time from family and friends, as writing demands a great deal of concentration and commitment. And the pressure only mounts as the deadline for submission to the publisher looms.

Nevertheless, an author is never truly alone. For instance, in my case, I am grateful to Clive Horwood of Praxis and Maury Solomon and her staff at Springer New York, who for the third time have entrusted their reputation to one of my writing proposals. I am also indebted to Dr. David M. Harland, who for the third time has turned my raw manuscript into a book. I must also mention Dr. Erik Seedhouse, Michel van Pelt, Dr. Philip T. Metzger, and Robert Zimmerman for expressing a positive recommendation to Springer for publication and for their counsel on layout and content. And, as usual, I thank Jim Wilkie for his eye-catching cover.

I cannot deny that I had several moments of frustration and doubt. My wife Monica was instrumental in dispelling them, even when she was busy earning her bachelor and master degrees. My parents, Pasquale and Maria, have always encouraged me in my various projects, particularly those concerning space exploration. In addition, by their interest and support, my friends, work colleagues, and acquaintances have all played a role in motivating me to write this book.

Acronyms

AFM	Additive Manufacturing Facility
APIS	Asteroid Provided In-situ Supplies
ARM	Asteroid Return Mission
AU	Astronomical Unit
BEAM	Bigelow Expandable Activity Module
CCD	Charged Coupled Device
CDR	Computed Dental Radiography
CMOS	Complementary Metal Oxide Semiconductor
FDM	Fused Deposition Modeling
FMD	Forced Metal Deposition
FLNG	Floating Liquefied Natural Gas
GE	General Electric
GPS	Global Positioning System
GRASP	Grapple, Retrieve, And Secure Payload
IOSD	International Organization for Space Development
ISS	International Space Station
ITER	International Thermonuclear Experimental Reactor
JPL	Jet Propulsion Laboratory
KREEP	Phosphate, Rare Earth Elements, Phosphorous
KRUSTY	Kilopower Reactor Using Stirling Technology
MEB	Molecular Beam Epitaxy
MEMS	Micro Electro-Mechanical Systems
MIT	Massachusetts Institute of Technology
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NEP	Nuclear Electric Propulsion

NTR	Nuclear Thermal Rocket
NIAC	NASA Innovative Advanced Concepts
OST	Outer Space Treaty
PEEK	Polyether Ether Ketone
RAP	Rapid Asteroid Prospector
SETI	Extraterrestrial Intelligence Institute
SLA	Stereolithography
SLS	Selective Laser Sintering
SMM	Small Manufacturing Machine
SMR	Small Modular Reactor
SPACE Act	Spurring Private Aerospace Competitiveness and Entrepreneurship Act
USSR	Union of Soviet Socialist Republics
VAD	Ventricular Assist Device
VASIMIR	Variable Specific Impulse Magnetoplasma Rocket
VICAR	Video Image Communication and Retrieval
WSF	Wake Shield Facility
WRANGLER	Weightless Rendezvous and Net Grapple to Limit Excess Rotation

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Space Exploration: What For?

WHAT FOR?

What is the purpose of space exploration? Why spend prodigious amounts of money to enable a few highly trained individuals to travel in space months for at a time in an inherently dangerous environment? Why devote taxpayer money just to send a small robot to snap pictures at the edge of the Solar System? Are not there more pressing, urgent conditions affecting human society that would benefit from such investments? You, or somebody you know – a family member, a colleague, an acquaintance – might have similar questions. They all hinge on determining whether space exploration is a worthy endeavor. If you are an advocate for space exploration, you might find these questions annoying. Why cannot people understand the importance of spaceflight, you might ask yourself? Why must they question it?

However, if we take an objective look at some numbers we might concur that these questions, and the detractors, might be onto something. Consider that, on average, a mission by the Space Shuttle cost some US$450 million; support and handling of the International Space Station costs between $3 and $4 billion per year; the New Horizons spacecraft that in 2016 showed us the jaw-dropping landscape of Pluto cost some $700 million; the car-sized Curiosity rover on Mars required some $2.5 billion to build, and more money is poured annually to continue its adventures on the Red Planet. Space exploration is clearly expensive, and perhaps the money could be put to better use in building hospitals and schools in developing countries, in eradicating cancer, and in obliterating plagues such as AIDS. Advocates of space do have an obligation to answer to these questions. Let us start therefore by analyzing the main rationales attributed to space exploration.

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Then we will weigh their value against our present reality and assess whether space exploration has any place in our society.

Rationales of Space Exploration: Geopolitics, Prestige, National Security

Ever since the Soviet Union orbited Sputnik on October 4, 1957, space exploration in general, and human spaceflight in particular, have portrayed a country's technological strength and manifesto for way of living. The race to the Moon is the perfect example. In the midst of the Cold War, President John F. Kennedy's call to reach our natural satellite was motivated more by a need to demonstrate that America was superior, in every way, to its rival on the other side of the "Iron Curtain".

In his Special Message on Urgent National Needs delivered to a joint session of Congress on May 25, 1961, shortly after the Russians flew Yuri Gagarin in orbit and America responded by sending Alan Shepard on a ballistic mission, Kennedy made this explicit: "If we are to win the battle that is now going on around the world between freedom and tyranny, the dramatic achievements in space which occurred in recent weeks should have made clear to us all, as did the Sputnik in 1957, the impact of this adventure on the minds of men everywhere, who are attempting to make a determination of which road they should take." He presented space exploration and its achievements as the yardstick to gauge the success of a nation's way of living. The "road" he referred to was the choice between freedom and tyranny, and that decision was to be based, among the other things, on the quality of a nation's space exploration program.

Kennedy continued: "Recognizing the head start obtained by the Soviets with their large rocket engines, which gives them many months of lead-time, … we nevertheless are required to make new efforts on our own. For while we cannot guarantee that we shall one day be first, we can guarantee that any failure to make this effort will make us last. … We go into space because whatever mankind must undertake, free men must fully share." Considering that there were only two contenders in the space exploration arena, the United States had better not be last, because that was what free men had to undertake. Nothing less than freedom was at stake.

Having charged his audience with pride, and appealed to the ideology of freedom so dear to any American citizen, Kennedy was now ready to deliver the final blow: "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth." How could anybody refuse such a commitment now that it was linked to everything that American society stood for! On July 20, 1969, Neil Armstrong, an American citizen, became the first man to set foot upon the Moon.

The example set by Kennedy would be followed by a number of his successors. For instance, despite an ever decaying public and political support for human-crewed spaceflight which curtailed the Apollo program and ended NASA's dreams of lunar exploration, President Richard M. Nixon made sure that approval for the Space Shuttle would be given. In fact, in August 1971, Caspar W. Weinberger, Director of the Office of Management and Budget, wrote a memorandum to Nixon expressing his concern "that our best years are behind us, that we are turning inward, reducing our defense commitments, and voluntarily starting to give up our super-power status, and our desire to maintain world superiority" and that hence "America should be able to afford something besides increased welfare, programs to repair our cities, or Appalachian relief, and the like." And the Space Shuttle was expected to enable America to reassert its superiority among nations and surge ahead in the exploration of space.

When NASA Administrator James M. Beggs met with President Ronald Reagan on December 1, 1983, he showed him a photo of a Soviet Salyut space station against the backdrop of the USA. At the State of the Union Address delivered before a joint session of Congress on January 25, 1984, another Kennedy moment was about to take place. The words would be different but the structure of the script remained the same. Reagan first appealed to the greatness of his nation: "Nowhere do we so effectively demonstrate our technological leadership. … Our progress in space, taking giant steps for all mankind, is a tribute to American teamwork and excellence." There was a nod to the values of the Free World relative to the closed communist Soviet Union: "And we can be proud to say: We are first. We are the best. And we are so because we are free." With his audience prepped for the next commitment in space, he said: "We can reach for greatness again. … Tonight, I am directing NASA to develop a permanently manned space station and to do it within a decade." Once again, national pride was a potent ally in initiating a complex and rather contested space program.

However, it would be more than 20 years before the assembly of the space station would start. And when on November 20, 1998, the first component was orbited it was not American but a Made-in-Russia module named Zarya. The political climate was profoundly different. The Soviet Union had ceased to exist in December 1991, and the need to demonstrate the superiority of the Free World over communism was irrelevant. With the fall of the USSR, the Russian space program was plunged into an existential financial crisis and the concern in America was that the cash-strapped engineers would offer their undoubted talents and capabilities to countries hateful of the United States. With the space station program running way over budget and teetering on the brink of cancelation, in his State of the Union Address on January 25, 1994, President Bill Clinton tackled the need to keep the Russian space workforce busy: "Russian scientists will help us build the International Space Station." Therefore, it is not surprising that since its inception the ISS has been criticized for being primarily a tool to maintain the post-Cold War détente and to showcase goodwill in international relations. Indeed, it is not uncommon at times of crisis for this multi-billion dollar collaboration at 400 km altitude to be hailed as evidence the two superpowers *can* still cooperate.

Consider the events involving the Russian annexation of Crimea in 2014. Despite the condemnation by the US and the European Union, and the economic sanctions that they then applied, Russia remains a partner in the ISS and routinely delivers supplies and personnel.[1]

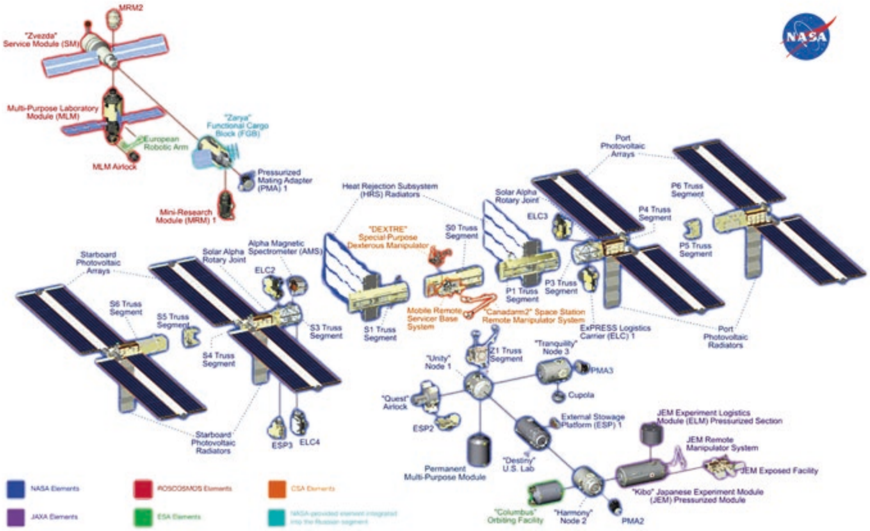

Figure 1.1 An exploded view of the International Space Station showing the individual components color coded by national contribution. The international cooperation in this venture is evident.

The umbrella of geopolitics has enabled defense and national security to become effective motivators for activities in space. Civilizations of any type, place, and time have recognized the benefit of being able to observe the movements of an approaching enemy. In fact, castles and villages, whenever possible, were built on cliffs, high hills, and mountains tops. And as soon as we began to master the art of flight, balloons and airplanes were used for reconnaissance of the enemy lines, and indeed far beyond. And in addition to determining the next defensive or offensive maneuver, an elevated point also allows the delivery of bombs, missiles and the like for a greater destructive impact. It is therefore easy to appreciate how space became the ultimate "high ground" for the observation of the enemy and formulating offensive actions. As early as 1951, Werner von Braun proposed a bomb-dropping space station, saying that a nation orbiting such a platform "might be in a position virtually to control the Earth". Perhaps he struck a chord with the US military, as on 16 March 1955 the United States Air Force officially ordered the development of an advanced reconnaissance satellite to

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[1] With the advent of commercial service providers such as SpaceX and Boeing, which are both developing spacecraft for crew transportation, the status quo might change radically.

provide continuous surveillance of "preselected areas" "to determine the status of a potential enemy's war-making capability". Not surprisingly, when Sputnik was launched 2 years later, the US military, as well as the general public, were swift to grasp the implications of that tiny sphere emitting a faint radio signal; namely that the Soviet Union might now have the unhindered capability to drop weapons, possibly nuclear, anywhere on Earth without warning.

Luckily, bombs have not yet been dropped from space, and no satellite has carried weapons.[2] However, flotillas of so-called spy satellites have been launched with ever-increasing capabilities in photo surveillance, early warning of missile launch, detection of nuclear explosions, electronic reconnaissance, and radar imaging. Such skills are no longer exclusive to the United States and Russia. These capabilities have proved their worth in conflicts or situations involving national security for the past six decades.

Rationales of Space Exploration: The Frontier

Throughout history, "the frontier" has been a potent lure motivating people to explore what lies beyond their comfort zone. This spirit has been present everywhere, from the mythological account of Ulysses, to the Far West, to the exploration of the poles just a century ago. As the acclaimed astronomer and science communicator Carl Sagan wrote: "We're the kind of species that needs a frontier – for fundamental biological reasons."

The online Oxford Dictionary defines "frontier" as "a line or border separating two countries" and also as "the extreme limit of settled land beyond which lies wilderness". With this explanation, it is easy to appreciate how space can be considered a frontier. It is the opposite of a life-laden settled planet. It is vast, lifeless, and wild. As the most difficult to reach and subject to our own will, space is the *ultimate* frontier. It is not by accident that in the 1950s, and for some time after that, you would hear and read about "the conquest of space". Compared to the more politically-correct "space exploration" a conquest did indeed instill feelings of dominating the harshest of the frontiers in the same manner that the western part of the United States was colonized.

The iconography of the frontier goes well beyond physical places, and penetrates deeper into the human psyche. The same Oxford Dictionary offers an additional telling interpretation: "the extreme limit of understanding or achievement in a particular area". Space exploration has furthered our comprehension of the most disparate mysteries of the Solar System and the Universe. For instance, it was the American-born physicist Lyman Spitzer who first proposed the carrying out of astronomical observations from orbit when in 1946 he published an intriguing

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[2] An interesting exception are the Soviet Almaz space stations designed for reconnaissance-gathering missions. They even had a small, fixed cannon that the cosmonauts would have used in the case of being approached by an enemy spacecraft.

scientific article entitled 'Astronomical Advantages of an Extra-Terrestrial Observatory'. He explained how the atmosphere hinders astronomical observation by absorbing most of the electromagnetic spectrum apart from that to which our eyes are sensitive. Furthermore, even the quality of optical observations is drastically affected by the daily and local changes of the atmosphere's physical properties, referred to by astronomers as 'seeing' conditions. The scheme that Spitzer concocted was to put a telescope in orbit around Earth to perceive the Universe at never-before-seen wavelengths. Sure enough, the first satellite applications, by both superpowers, were for astronomy. Since then, there have been a steady stream of ever-sophisticated space-borne telescopes.

At the same time, robotic probes have been posted to every major body of the Solar System, revealing alien vistas that had previously only been imagined in the pages of science fiction publications. In some cases, robots have even provided an up-close in-situ studies of such landscapes. However, the only celestial body to have been visited by humans is the Moon, by the Apollo astronauts. Thus far, all efforts to renew human exploration have failed the funding hurdle. Since the tragic loss of the Space Shuttle Columbia in February 2003, every major space agency has been trying to initiate plans for either a return to the Moon or to achieve the first boot prints on Mars. Among the top reasons presented to justify such ventures is the need to improve our understanding of these alien worlds.

There is another area of the frontier definition that we must reflect on: "the extreme limit of … achievement in a particular area". This is a frontier in what we, as a species, can do. Humans have always striven to accomplish ever grander projects and we have used them as yardsticks in demonstrating our ability to tame nature to our goals. The same attitude is also experienced on an individual scale, as most of us feel the need to embark on projects or hobbies that give us a sense of accomplishment and provide the confidence that we are capable of doing even better. It is not surprising that President Kennedy said: "We choose to the go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because the goal will serve to organize and measure the best of our energies and skills." The exploration of space is difficult and challenging. It does require an extraordinary effort to concoct complex machinery to harness in a controlled manner the equivalent energy of an atomic bomb, or to precisely arrange for a space probe to rendezvous with a small body billions of kilometers away after a journey lasting years. Consider the fly-by of Pluto by NASA's New Horizons spacecraft, the European Space Agency's Rosetta mission's encounter with the 67P/Churyumov-Gerasimenko comet, and more recently the Japanese Space Agency's Hayabusa 2 probe which landed two small hopping rovers on the surface of the asteroid 162173 Ryugu. Another good example is the intricate sky-crane apparatus devised to safely and precisely land NASA's Curiosity rover on Mars, something never previously attempted, difficult to test on Earth, and had only one chance to work upon reaching its target. Even for the layman such accomplishments raise awe, marvel, and a sense of pride at what humans can achieve.

At times, it can inspire action. It frequently gives us confidence that we can resolve thorny and demanding problems. It is not unusual to hear expressions such as “if they were able to go to the Moon then they can also [substitute a problem familiar to you]”. Time and again, the public relations departments of the national space agencies levy heavily on our natural desire to seek a grand challenge as a reason for a return to the Moon or to send people to Mars. Quotations from Werner von Braun such as: “I have learned to use the word ‘impossible’ with the greatest caution” or Robert H. Goddard’s “It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow” really do nurture such spirit.[3]

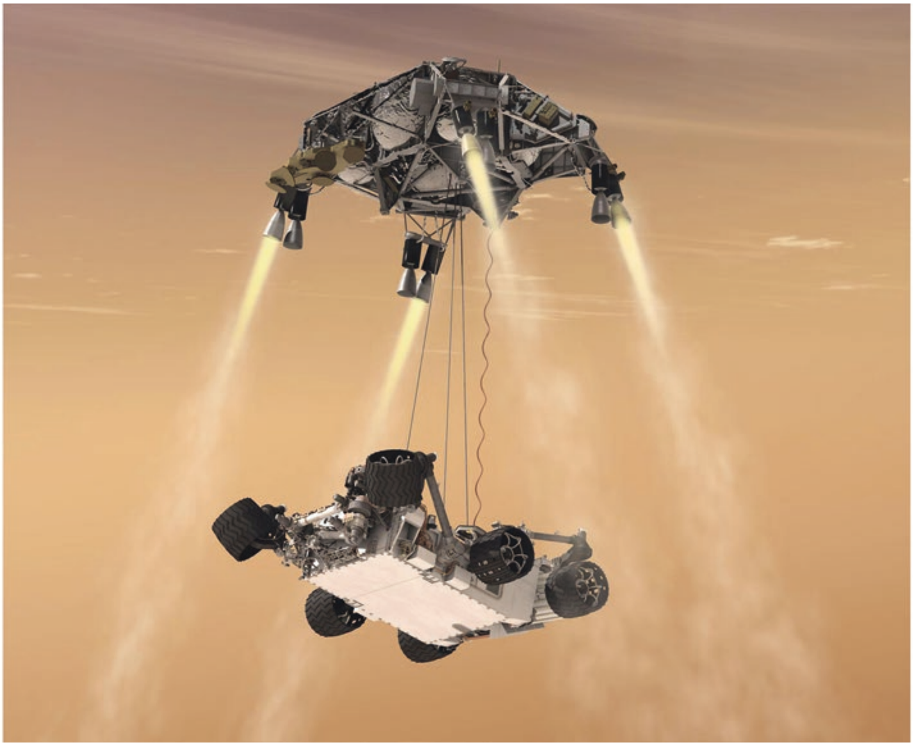

Figure 1.2 An artist’s impression of the final moment before touchdown of the Curiosity rover on Mars. The so-called sky-crane consisted of a platform that was stabilized by four clusters of small rocket thrusters which fired just above the surface, while a winch lowered the rover gently to the surface at the end of a rope.

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[3] It is worth recalling that both men are considered the fathers of modern rocketry in Germany and the United States, respectively.

The need to explore and advance the frontier has repeatedly protected our species from events that might otherwise have placed its survival at risk. There is abundant archaeological evidence of how large and small groups have undertaken migrations beyond their frontiers to find better places to settle. Often it was in response to natural events or human-made circumstances, such as war or overexploitation of resources as a result of runaway population growth (more on this at the end of the chapter).

The same rationale applies to space exploration, particularly in terms of a human presence in space. The renowned sci-fi writer Larry Niven once said: “The dinosaurs became extinct because they didn’t have a space program. And if we become extinct because we don’t have a space program, it will serve us right!” This might sound like a joke, but the demise of these giant reptiles has been attributed to an asteroid striking our planet. As we track more and more such rocks passing by, the risk of another such cataclysmic event is no laughing matter. Recall the 2,000 square kilometers of Eastern Siberia where some 80 million trees were razed on June 30, 1908, by either an asteroid or a comet exploding with the force of a large nuclear bomb over the Stony Tunguska River area. On February 15, 2013, another space rock detonated with a much smaller blast over the Chelyabinsk area in the Southern Urals of Russia. Although neither event produced human casualties, the destruction they unleashed are stark reminders that we cannot dismiss such threats. It is therefore not surprising that expanding our capability to detect and chase what lies out there is gaining traction both within and beyond the space community.

Others have taken a more aggressive stand by proposing a modern version of our ancestors’ migrations: the colonization of space. Two movements share the same goal with different destinations in mind. The first one was started by Gerard K. O’Neill, a physicist at Princeton University, New Jersey. In the mid-1970s, O’Neill called for a program to build vast cylinders in space to sustain millions of people in conditions not dissimilar to a typical American suburb. Such colonies would draw electrical power from the inexhaustible energy of the Sun and would gain independence from Earth by developing their own industries using lunar or asteroidal resources. In fact, they would sell their own products once full self-sufficiency was achieved. Since then, colonies in space in every sort of shape and size have been subject to serious consideration, at least from a technical perspective.

The alternative is to create an artificial habitat on the surface of a celestial body. Although the Moon is the closest, and we have already shown that we can reach it, the destination that space agencies, individuals, and space advocacy societies yearn for is Mars. For example, one of the most prominent individuals actively championing Mars is Elon Musk. He has used his personal fortune to create SpaceX, a rocket company whose stated purpose is to make humankind a

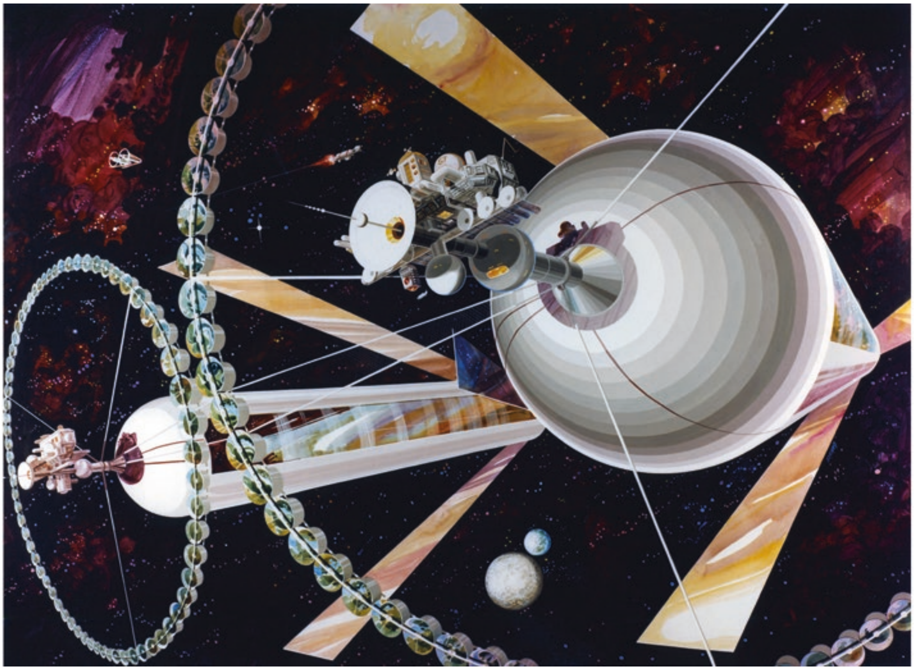

Figure 1.3 An artist's depiction of a pair of O'Neill cylinders, each capable of housing millions of people.

multi-planetary species. As of writing, SpaceX has already begun construction of a massive rocket ship with the objective of sending the first humans to Mars. Robert Zubrin, the founder of the Mars Society, has been strongly advocating for a Mars mission for several decades now. The work of the Mars Society to experiment with available technology in order to make a Mars mission feasible is both admirable and inspiring.

A major asteroid impact is not the only extinction risk facing the human species. A nuclear war, use of biological weapons, dwindling of resources due to overpopulation, societal collapse, and so on, are all reasons for a human migration into space. And in a few billion years our Sun will evolve into a 'red giant' star. Its inflated surface will swallow up the inner planets and the resulting conditions on Earth will render all life impossible. Thus, irrespective of the type of threat, the human colonization of space is heralded as an insurance policy against extinction. Furthermore, it can also provide the opportunity to give humankind a chance to develop a better society, opportunities for experiments in cultural diversity, even Utopian, as envisioned by science author T. A. Heppenheimer. As he wrote in his book *Colonies in Space*: "Some of these people will form specialized communities and will develop (or bring with them from Earth) their own characteristic ideas of how life should be lived, how a community should be organized. On Earth it is difficult for these people to form new nations or regions for themselves. … But in space it will become easy for ethnic or religious groups, and for many others as well, to set up their own colonies. … Those who wish to found experimental communities, to try new social forms and practices, will have the opportunity to strike out into the wilderness and establish their ideals in cities in space. This, in the long run, will be one of the most valuable results from space colonization: the new social or cultural forms people will develop."

Such possibilities also occurred to O'Neill in his masterpiece *The High Frontier*: "What chances will we have, though, here on an Earth ever more crowded and hungrier for energy and materials, to allow for diversity, for experiment, for groups to try in isolation to find better lifestyles? What chances for rare talented individuals to create their own small words, of home and family, as was so easy a century ago in our America as it expanded into a new frontier? … The most chilling prospect that I see for a planet-bound human race is that many of these dreams would be forever cut off for us."

This comes full circle with the human need to reach and tame the frontier. Reaching and settling the frontier is what Robert Zubrin describes as "humanity's greatest social need. Nothing is more important … Without a frontier to grow in … the entire global civilization based upon values of humanism, science, and progress will ultimately die."

Answering the urge to conquer the frontier, an insurance policy for humankind, a chance to create a better society that has learned from the past, and infusing confidence in our ability to engage in seemingly impossible endeavors, are all tightly intertwined in bestowing a strong rationale for space exploration.

Rationales of Space Exploration: Searching for ET

"But where is everybody?" Italian physicist Enrico Fermi asked at a luncheon in Los Alamos in the summer of 1950. As recalled by his colleagues, Fermi was questioning the lack of evidence for extraterrestrial civilizations. Known as the Fermi Paradox, this has spurred many a debate about the existence of other intelligent forms of life in the galaxy. The Search for Extraterrestrial Intelligence Institute (SETI) was established in 1984. Far from being a laughable excuse to look for little green aliens, the institute is a serious "private, nonprofit organization dedicated to scientific research, education, and public outreach" with the mission "to explore, understand, and explain the origin and nature of life in the universe, and to apply the knowledge gained to inspire and guide present and future generations".

Among the original board of trustees was Dr. Frank Drake, a radio astronomer at the National Radio Astronomy Observatory in Green Bank, West Virginia. In 1961 he published an equation, known as the Drake Equation, which grouped those factors that should be appraised in estimating the number of civilizations in our galaxy capable of radio communications. As explained by the SETI Institute, the Drake Equation "is a simple, effective tool for stimulating intellectual curiosity about the universe around us, for helping us to understand that life as we know it is the end product of a natural, cosmic evolution, and for making us realize how much we are a part of that universe".

There is no doubt that we have become obsessed with the search for extraterrestrial life, be it intelligent or not. For instance, robotic exploration of Mars is predominantly focused on this topic. The two Viking probes landed on the Red Planet in the summer of 1975 and not only snapped panoramic vistas and close-up pictures of the soil, but also "conducted three biology experiments designed to look for possible signs of life". The Spirit and Opportunity rovers landed on Mars in early 2003 to carry out extensive soil sampling. In doing so, they unearthed "evidence of ancient Martian environments where intermittently wet and habitable conditions existed". These are circumstances considered suitable for the development of life. The small Phoenix lander spent three months on Vastitas Borealis, an arctic plains near the north pole, digging into a near-surface ice-rich layer looking for evidence "about whether the site was ever hospitable to life". The car-sized Curiosity rover is currently surveying Gale Crater to answer one question: "Did Mars ever have the right environmental conditions to support small life forms called microbes?" In 2020, a twin of Curiosity is scheduled for launch, and with additional tools such as a drill it will take "the next step by not only seeking signs of habitable conditions on Mars in the ancient past but also searching for signs of past microbial life itself".

The search for life has extended well beyond the confines of the Solar System, and is actively pursued both on the ground and in space. Most notably, the Kepler Space Telescope has discovered thousands of extra-solar planets. Thus far, no planets have been found to host all the conditions deemed necessary for life to occur or survive, but the search for a "second Earth" continues. There is no doubt that the search for another civilization, the quest for another Earth, and the desire to find out whether life on Earth is unique, all play major roles in assigning considerable human and financial resources to space exploration.

Rationales of Space Exploration: Spinoff and Satellite Applications

The use of space for applications directly affecting our daily lives is well documented, and perhaps the easiest to understand. Weather forecasting, telecommunications, and GPS-based services are among the most ubiquitous accomplishment of the Space Age, so much so that it is easy to forget they rely on multi-million dollar spacecraft orbiting Earth. Environmental monitoring conducted by satellites specialized in analyzing one or more peculiar aspects of our planet's environment are perhaps less popular in daily jargon, but they play a paramount role in understanding and better managing our world and its limited resources on behalf of future generations.

Satellite applications fulfill well-defined tasks, but the term “spinoff” is defined as “a by-product or incidental result of a larger project”. In NASA parlance, a spinoff is “a commercialized product that incorporates NASA technology or expertise”.[4] These include: products designed to NASA specifications initially for use by NASA and then commercialized; products that are developed as a result of a NASA-funded agreement or know-how acquired by collaboration with NASA; products that incorporate NASA technology in their manufacturing; products that receive significant contributions in design or testing from NASA personnel or facilities; products that are entrepreneurial endeavors by former NASA employees whose technical expertise was acquired while in the employ of the agency; and products that are developed using data or software made available by NASA. With this broad definition in mind, let us consider several examples of NASA spinoff.

In the 1960s, NASA JPL engineer Eugene Lally proposed the use of a mosaic of photosensors to digitize light signals and make still images. In the following decades, NASA toyed with this idea up to when the Charged Coupled Device (CCD) sensor was developed. This gave the scientific community the opportunity to equip detecting instruments with a small, lightweight, and robust image sensor suitable for the extreme environment of space, most notably for astronomical observations. In fact, with a CCD apparatus, high-resolution images can be recorded and held in a solid-state long-term storage ready for transmission to Earth at the next communications opportunity. The CCD enjoyed universal success from reconnaissance satellites to the Hubble Space Telescope, and once released into the commercial realm in the form of digital cameras it transformed the market. Generally speaking, an image sensor contains an array of photodetectors called “pixels” that collect photons.[5] The photons entering the pixel are converted to electrons, generating signals that a processor can assemble into a picture. CCD-based pixel arrays operate like a bucket brigade, with the light-generated charge from each pixel passing along the entire array of pixels to the corner of the chip, where it is first amplified and then recorded. But CCD sensors require a lot of power and an extremely high efficiency of charge transfer. These difficulties are compounded when the number of pixels increases for higher resolution or when video frame rates are sped up.

When in the early 1990s NASA adopted the banner of “faster, better, cheaper”, JPL engineer and CCD-expert Eric Fossum recognized that it was time to improve the CCD sensor by using the Complementary Metal Oxide Semiconductor (CMOS) technology, a well-known process used since the 1960s in the manufacture of microprocessors of ever diminishing size and with an ever increasing number of transistors. Using this, he was able not only to produce a sensor that had the same performance as an equivalent CCD-based sensor, he was also able to integrate almost all of the associated electronics for timing and control systems, for analog-to-digital

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[4] As a matter of fact, you can replaced NASA with any other national space organization.

[5] Pixel is a contraction of “picture element.” Interestingly, the term was coined in 1965 by another NASA JPL engineer, Frederic Billingsley.

conversion, and signal processing. Thus was born the “camera on a chip” and with it the new term of CMOS Active Pixel Sensor (CMOS-APS). As Fossum explains, “active pixel means that the pixel’s got an active transistor in it, an amplifier”.

By allowing the integration of a complete imaging system onto a single piece of silicon, CMOS-APS technology has improved miniaturization, enhanced reliability, increased signal integrity, improved speed, and significantly cut power consumption to 1/100th of the equivalent CCD sensor. The fact that it shares the same manufacturing platform of microprocessors and memory chips means that crafting CMOS sensors is more cost-effective and simpler than CCDs. This facilitated smaller camera systems that included an architecture to protect the electronics from the radiation in the space environment.

Fossum soon recognized that this technology had the potential to address a wide range of non-space applications. In 1995 he and some coworkers founded Photobit for the commercial exploitation of the CMOS-APS technology. In the ensuing years, they designed specialized sensors and licensed them to colossi such as Kodak and Intel. The commercial breakthrough arose when cell phones became the “killer application” that drove manufacturers towards ever-smaller devices with longer battery lives. Soon, the CCD-based devices could no longer compete with the falling costs and the increasing quality, even when size and power were not priorities. Now, apart from niche markets, virtually all digital still and video cameras use Fossum’s invention.

But CMOS-based imaging technology is not limited to our leisure activities, it has established itself in applications such as medical imaging with X-rays. In fact, X-ray radiography on film has a number of downsides, most notably the cost of film material, difficulties in storing the exposures because they degrade over time, disposing of the chemicals used in development, and, last but not least, subjecting the patient to a high dose of radiation.

To overcome these drawbacks, the medical community started to apply the NASA-developed CCD technology to digital imagers that combine a higher sensitivity with a lower dose of radiation. Because there is no need to develop a film, this eliminated the handling precautions for toxic chemicals. The fact that the turnaround is much faster meant that X-ray technicians and other medical staff did not have to wait for film to be processed. Furthermore, a digital image can be manipulated to improve the diagnosis and to communicate problems to the patient. There are, however, some nuisances. For instance, X-rays cannot be focused with lenses. And the array of pixels for a digital X-ray imager must have the size of the object being observed. That means a lot of pixels. A CCD-based array has to transfer each pixel’s charge from pixel to pixel through the array with virtually no losses. The greater the number of pixels, the greater the overall potential for loss, with the risk of reducing the resolution that might lead to an error in characterizing vital details of a patient’s health.

This prompted Schick Technologies to approach Photobit in 1995 and obtained an exclusive license to develop a CMOS-APS dental imager. Named Computed

Dental Radiography (CDR), this product employs an electronic sensor in place of X-ray film to generate sharp and clear images that appear on a computer screen within 3 seconds and can be enlarged and enhanced as necessary to identify problems. It is compatible with virtually all X-ray tubes, seamlessly integrates with existing practice management systems, and even permits the correction of underexposed radiographs. The low power requirements of CMOS sensors enabled the company to develop miniaturized battery-powered apparatus, for example intraoral X-ray sensors that fit inside the mouth and significantly improve a patient's comfort. CMOS imagers also allow the radiologist a low-resolution preview, or check for exposure, using a quick readout from a few pixels at minimal energy, whereas a CCD-based imager would have had to read out the entire array.

NASA has also devoted considerable effort to developing software packages that accurately manipulate data received from planetary probes and space telescopes. In 1966 NASA set up the Image Processing Laboratory at JPL. Since then, evolution of the NASA-invented Video Image Communication and Retrieval (VICAR) software has laid the groundwork for understanding images ranging from the Voyager missions to New Horizons. This same software package is now playing a vital role in the early diagnosis of atherosclerosis in which a buildup of cholesterol and fatty substances in the arteries, along with arterial hardening, restricts the blood supply to the heart and hampers oxygen flow. Atherosclerosis is known as the "silent killer" because it does not display obvious symptoms prior to one or more of the major arteries becoming so congested that the problem arises. Often this results in death due to cardiac arrest with little time left for the medical personnel to reach and reanimate the victim. One clear sign of atherosclerosis is achieved by examining the thickness of the arteries, because this is the initial stage of the process. This is why Medical Technologies International (MTI) Inc., of Palm Desert, California, has patented ArterioVision, a software package based on the VICAR software. After an ultrasound inspection of the carotid arteries, ArterioVision gives an accurate measurement of the thickness of the inner two layers, the intima and media.[6] By knowing the real condition of their artery network, patients can appreciate the need to change their lifestyle with dietary modification and exercise. This technology is now being used worldwide.

In designing its first spacecraft at the beginning of the Space Age, NASA realized that the onboard electronics would be subject to either soaring or freezing temperatures if they were maintained facing either towards or away from the Sun. Electronics does not perform well when subjected to extreme temperatures. One remedy is to rotate a spacecraft in order to even out its internal temperature. But if the mission objectives require holding a given attitude, the spacecraft will have to endure an

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[6] The selection of the carotid arteries for this test stems from the fact that they are the largest blood vessels closest to the skin surface and are therefore easy to examine without requiring an invasive procedure.

extreme variation in temperature between its Sun-facing and the space-facing sides. One option is to use heat pipes. In its most basic form a heat pipe is a sealed tube with an internal porous wick distributed along its length and a volatile liquid in thermodynamic equilibrium with its vapor. As heat is applied to one end of the pipe, the liquid evaporates and is displaced to the cold end, where it recondenses. At this point, the liquid withdraws into the wick to produce a pressure gradient that transfers the liquid back to the warm end. If one end is kept warm and the other is kept cold this process will operate for as long as there is sufficient liquid. It is an elegant way of carrying heat away without involving moving parts and without drawing electrical power. Heat pipe technology comes in a variety of shapes and sizes. It is merely one part of the larger set of systems for passive thermal control.

In 1970 Thermacore was founded in order to apply this technology outside of the space industry. One field that welcomed it was electrosurgery in which an electrical current is used to cut, coagulate, desiccate, or fulgurate a biological tissue. It greatly benefits the patient because of a more precise localized cut and reduced blood losses. A common apparatus is the bipolar forceps, a two-pronged tool that uses electricity to cauterize or ablate tissue between its tips. The connection with space exploration is not obvious, but bipolar forceps share the same heat management issue that face a spacecraft's electronics. The problem is that the electricity that generates the heat in the forceps can damage the surrounding tissue, sometimes causing it to stick to the heated tips. For example, in working on a person's brain you definitely want to burn away as little gray matter as possible. By exploiting their work for the space industry, Thermacore decided to embed extremely thin heat pipes into the bipolar forceps tips. The challenge was to provide sufficient heat transport capability within such a small volume and retain the ability to operate against gravity.

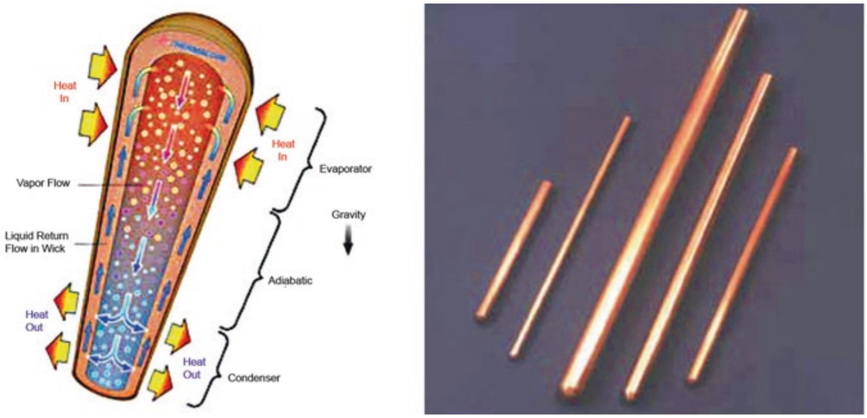


Figure 1.4 Heat pipes can transport heat from areas that are too hot and deliver it to where it is needed. Thermacore makes them in a variety of sizes and configurations for different applications, but they all employ the same basic design.

In addition to tools for brain surgery, Thermacore has improved robotic surgery systems which utilize lasers, PET-CT scanners, devices to ablate cancerous lesions, devices for DNA, blood analyzers, and many more applications.

A life-changing event can enable us to see things from a different perspective. It happened to NASA JPL engineer David Saucier, who suffered a heart attack in 1983 that resulted in a heart transplant the next year. He was lucky. Many people die while awaiting a suitable donor. Although Saucier and Dr. Michael DeBakery, the surgeon at Baylor College of Medicine that performed the transplant, worked in completely unrelated fields, they were both experts in fluid pumps. The former knew the inside-out workings of the propellant turbopump of the Space Shuttle Main Engine and the latter was an expert in the human heart that pumps blood around the body.

The two determined to combine their knowledge and develop a pump that would buy time for patients with congestive heart failure while a donor was sought. Saucier and DeBakery, along with others at their respective institutions, began working part-time. They developed a miniaturized battery-powered pump measuring 1 x 3 inches and weighing just 4 ounces. By assisting a critically ill patient's heart to pump blood until a heart became available for transplant, it forms a "bridge to transplant". There were already such Ventricular Assist Device (VAD) but they were cumbersome and weighed about 1 kg! The reduced size and weight of the NASA-designed VAD made it suitable for implantation into a patient's chest, even a child's. When it was realized that friction and pressure in the axial rotary impeller could damage the blood cells, it became necessary to optimize the pump. Help came from Cetin Kiris and Dochan Kwak at NASA's Advanced Supercomputing Division at the Ames Research Center in Moffett Field, California. Using the same computational fluid dynamic software that simulated the fluid flow through the Space Shuttle Main Engine's turbopumps, they were able to optimize the design of Saucier and DeBakery's VAD to eliminate its deficiencies and make it even better.

In 1996 NASA patented the device and granted exclusive production license to MicroMed Technology Inc., in Houston, Texas. Mr. Dallas Anderson funded further development of the NASA invention to treat critically ill heart patients. In November 1998, a 56-year-old male was the first person to receive the device. Since then, this MicroMed DeBakery VAD has been implanted into hundreds of patients around the world, helping to keep them alive while they await a heart transplant. In 2002, the *Spinoff* magazine regularly published by NASA reported, "because of the pump's small size, less than five per cent of the patients implanted developed device-related infections, compared to an approximate 25 per cent infection rate for larger VADs. Additionally, MicroMed's VAD can operate up to eight hours on batteries, giving patients the mobility to do normal, everyday activities."

SPACE EXPLORATION: WHAT IS IT GOOD FOR?

Having briefly elaborated a number of rationales, can we say that space exploration is worthwhile?

Satellite applications have become an indispensable part of modern life. If denied them, even briefly, we become frustrated. We might even panic! The possibility of fast communications has made possible and accelerated globalization, making the world a smaller place. In the not so distance future, even more services will be available thanks to projects to create large satellite constellations in low-altitude orbits which will beam internet services sufficient to allow even rural areas in developing countries to benefit. Environmental monitoring from space has a large influence on a country's economy, allowing its institutions to obtain a synoptic view of the condition of the landscape and resources and hence plan for the most optimal exploitation and organization. Certainly there is no need to emphasize the benefits generated by weather monitoring, or analysis of the climate in terms of the main drivers in the sea, land, and atmosphere. Likewise, satellite reconnaissance for intelligence gathering purposes has proved an effective tool for national security, not only in fighting wars but also addressing the threats of global terrorism.

We cannot deny that exploration is a human trait, seemingly specifically coded into our DNA, that has driven our civilizations and societies for millennia. And nor can we resist the lure of the frontier, whether that be a location to reach or an achievement to accomplish. Surpassing in complexity and magnificence is a pure human trait that has served us well through the ages. The need to feel proud of our achievement is again as old as human history. You can think about the Egyptian obelisks, or the Assyrian relief panels, or any other civilization that recorded their successful battles and conquests. In the 20th century, the United States of America celebrated its existence by sending men to walk on the Moon and return with rock samples.

While it is undeniable that societies and civilizations of any complexity throughout history have expanded their territory, the urge to explore was actually the prerogative of a small number of individuals. That is to say, we may all have the explorer gene but it is active in only in a few of us.

As a point in case, consider that even the mighty Apollo program did not enjoy an unconditional endorsement, despite the monumental media and PR machine favoring it. In October 1965 a Harrison poll asked: "If you had to choose, do you think it more important or less important to spend 4 billion a year on the space program than to spend it on reducing the national debt?" Some 54% selected the latter option. Four years later, on the eve of the first lunar landing, the percentage who favored redirecting funding to recover the national debt rose to 56.4%. Such results are not surprising if we consider that the political nature of the whole endeavor had not escaped the American public's attention. For instance, in October 1964, in response to a survey asking "Do you think the U.S. should go all out to beat the Russians in a manned-flight to the Moon, or don't you think this is too important?", 66% replied that beating the Russians was "not too important" and 8% did not know how to answer. Another survey several months later asked "Does it matter a lot to you that the Russians have been ahead of us in our space program?" and a majority of 54% of respondents said it did not matter at all.

The same goes for breaking frontiers of knowledge regarding the mysteries of the Universe. It is enthralling to see close-up pictures of Pluto or discover the origin of a gamma ray burst, but again such scientific curiosity does not belong to everybody. And in any case, not all scientifically inclined people will necessarily possess an interest in astronomy. What about finding signs of present or past extraterrestrial life? In January 2004, after the successful landings of the Spirit and Opportunity rovers on Mars, a poll carried out by Gallup for CNN and *USA Today* asked "Do you think it is worthwhile for the United States to find out whether there were ever living creatures on Mars, or not?" A narrow majority (54.4%) felt it was not worthwhile. While discovering life on Mars would be remarkable from an academic and perhaps philosophical point of view, investing large human and financial resources exclusively for this purpose seems too weak a justification for space exploration and merely an excuse to gratify the scientific community that harbors such an interest.

Although there are other examples, it is evident that the real "elephant in the room" is the failure to capture support from a large section of the general populace. You may including yourself among the skeptics. It is the case that the exploration of space is too far removed from the everyday reality of normal people who have to struggle to make ends meet in our increasingly unstable economic and working environments. Rises in inequality and the technological displacement of work make living difficult for normal people. As a result, the rationale for sending a few selected individuals into space does not earn much support. Indeed, it can create resentment for what appears to be a useless expenditure that could be better employed to enhance life on Earth. The argument to colonize space or the surface of a celestial body as an insurance policy has merit, but the chance of being hit by an asteroid large enough to risk the extinction of the human race is so remote as to be readily dismissed from our minds. Our brain is wired to react to situations that pose an immediate danger, not to circumstances that might gradually develop into one. As an example, consider how great civilizations such as the Romans, the Maya, the Khmer Empire, to name but a few, flourished over a long period of time and then suddenly collapsed. The signs of collapse manifested themselves slowly, and when the point of no-return was reached it was too late to recover.

Furthermore, the usual rationales advanced for spaceflight are always presented in the context of developed countries. The vast majority of humankind live in conditions affected by poverty, malnutrition, violence. Spaceflight is the least of their concerns! How crucial could it be to a mother seeking food for her children to know that space could help our species to survive extinction? It is too far detached from her immediate needs. The "hierarchy of needs" theory proposed by psychologist Abraham Maslow in his 1943 paper 'A Theory of Human Motivation' places physiological necessities and safety as the foundation for any other demand in life, such as self-actualization deriving from, for instance, exploration and discovery. This is applicable to anybody, regardless of their upbringing or their country's gross domestic product. So, is space exploration worth the effort?

A SPACE PROGRAM WORTH UNDERTAKING

I have been an advocate for space exploration for as long as I can remember. At first, it was unalloyed admiration for the extraordinary feats of the brave astronauts and the talented engineers at prestigious national institutions, but then I began to wonder about the justification for space exploration. For sure, the motivations presented above have enabled six decades of continued accomplishments in the space arena, and continue to drive us in that direction. This is especially the case for satellite applications, national security intelligence, surveying the cosmos and visiting the bodies of our Solar System. But I believe we can do much more. In particular, we can convert space from being a mere destination to satisfy mere scientific curiosity, into a resource to facilitate human activities undertaken for the benefit of Earth, the only home we currently have that is capable of sustaining a biosphere and thereby our species.

In his *The High Frontier*, Gerard K. O'Neill wrote: "In my opinion, the long-term goals we should set relevant to space habitability should only be those with which nearly every rational human being, possessed of good will towards others, could agree. I think that the following goals satisfy that criterion and that they should be our most important goals not only for humanitarian reasons, but for our own self-interest.

1. Ending hunger and poverty for all human beings.
2. Finding high-quality living space for a world population.
3. Achieving population control without war, famine, dictatorship or coercion.
4. Increasing individual freedom and the range of options available to every human being."

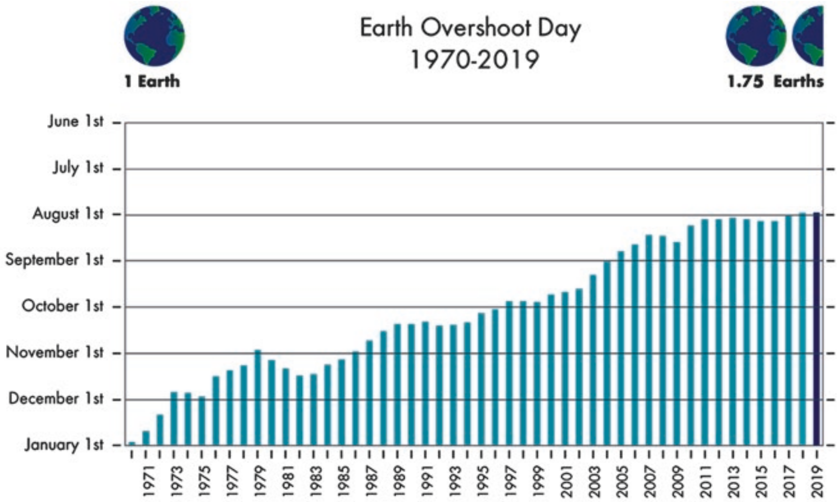
He also made a case for "unlimited low-cost energy available to everyone" and "unlimited new materials sources, available without stealing or killing or polluting". Although this sounds like science fiction dreaming, it is my desire throughout the next chapters to demonstrate that a properly organized space program can transform, in part, such beliefs into reality, and furthermore that doing so is not beyond our present-day technological capabilities.

A great many problems affect our modern way of living, and our environment, on scales ranging from local to global. One goes under the name of Ecological Footprint. Developed by Mathis Wackernagel and William Rees at the University of British Columbia, Canada, in 1990, this is intended to compare actual human consumption of renewable resources and ecological services against nature's supply of such resources and services. It measures how fast we are consuming the resources of nature and are dumping waste relative to how fast nature can generate new resources and absorb our waste. In this sense, Ecological Footprint is an accounting system of our demands for natural resources versus what nature can effectively supply and produce (also known as biocapacity). More specifically, biocapacity is defined as a measure of the existing biologically productive area which is capable of regenerating natural resources in the form of food, fiber and timber, and of providing carbon sequestration. It is measured in relation to five categories of use, namely: cropland, grazing land, fishing grounds, forest land, and built-up land.

Both biocapacity and Ecological Footprint are expressed in a productivity-adjusted hectare-equivalent unit called a global hectare (gha). One gha represents a biologically productive hectare with world-average productivity. Conversion from actual land areas to global hectares is by means of country-specific yield factors and equivalence factors. This normalizes highly productive areas such as tropical forests and low productivity areas such as alpine deserts.

In layman's terms, you can also envisage Ecological Footprint as an indicator for a minimum condition of sustainability for our civilization and whether our consumption is sustainable by the biological threshold defined by the planet's biocapacity. For this reason, Ecological Footprint is widely applied in the monitoring of ecological resource use and degree of sustainable development. An insightful additional parameter is Earth Overshoot Day, which is the date in a given year when humanity's annual demand on nature exceeds what the ecosystems can regenerate in that year. For instance, in 2019, Earth Overshoot Day was July 29th. Rather alarmingly, this date is arriving earlier year by year.

Simply put, humans are consuming more than the Earth's ecosystem can tolerate. We are effectively borrowing biocapacity income production from future generations. This draining of Earth's savings account can continue only until the reserves are gone. According to calculations, as of 2019, humankind is currently using nature 1.75 times faster than the ecosystem can tolerate. It takes the biosphere one year and eight months to regenerate what we deplete in a year. To express this another way, we would require at least 1.75 Earths to maintain our present-day consumption and waste disposal.



Source: Global Footprint Network National Footprint Accounts 2019

Figure 1.5 A plot of Earth Overshoot Day for the last 50 years. The few visible dips do not correspond to years in which intentional policies were activated to limit our impact on nature, they coincide with years of major economic crises, such as the 1973 oil crisis, the deep economic recession in the USA and many of the OECD countries during 1980-1982, and the global economic recession of 2008-2009.

It is not surprising that geoscientists and biologists argue that we have transitioned into a new geological epoch named the Anthropocene. This is because anthropogenic activities have profoundly changed every aspect of the environment, including loss of biodiversity, ocean acidification, soil erosion, deforestation, and other signs of climate change. It is the case that planetary modifications to the environment and climate have occurred throughout our planet's history, but they have never been concentrated in the human timescale. Instead of occurring slowly over millennia, if not millions of years, they are manifesting within decades as a result of the pressure imposed by one single species, namely humankind!

There are several drivers for these dramatic changes. One is the growing demand for mineral resources to feed the material-hungry manufacturing industries that satisfy our daily needs and wishes. Simply put, mining resources is akin to an invasive surgical procedure that leaves deep scars that are difficult to fully heal. Resource mining entails moving humungous amounts of soil, and makes use of heavily polluting chemicals and physical processes in separating the precious resource from the waste material. Mining areas are usually peppered with large pools of contaminated water awaiting treatment (if that is feasible, at all) and dumps of remaining residues. The landscape around any significant mining activity is profoundly changed, and not for the better. Similarly, the manufacturing industry that turns raw materials into goods and commodities invariably pollutes its surrounding environment. To borrow from acclaimed science fiction writer Robert A. Heinlein, the second law of thermodynamics is a harsh mistress. Matter and energy cannot be created, only transformed, and the process incorporates losses in the form of heat, incomplete reactions, waste, and so on. The environment, water, land and air accommodate the curse of the second law of thermodynamics. Collectively, such energy and material losses are labeled pollution. Earth's ecosystem is able to assimilate pollution. Every living organism and biological process contaminates its surroundings to some extent. And as the saying goes, one's trash is somebody else's treasure. Nature is smart, and its many forms of life are symbiotic, feeding on each other's wastes. For instance, animal poo is manipulated by the microorganisms that render soil fertile and allow fresh and nutritious vegetation to grow for herbivorous animals. One of the most essential wastes that nature produces is oxygen, emitted by the photosynthesis process of plants. Oxygen is vital to all animals having aerobic respiratory apparatus, including ourselves. Furthermore, the carbon dioxide that animals exhale from their lungs is the sustenance that plants require. In nature, things work in cycles of give and take, and an equilibrium state sustains the biosphere overall. The difficulty arises when something goes haywire.

The problem with human-induced pollution is that the amounts and rates of waste production and discharge have far surpassed the capability of the biosphere to absorb, neutralize, disassemble, and transform what we are throwing at it. This predicament is further complicated by the production of elaborate substances that nature would never have made on its own, such as plastics and mixtures of rare and heavy metal elements such as are used in electronic devices.

Earth's biosphere acts as a self-regulating organism that seeks to defend itself. This is the Gaia hypothesis postulated by British scientist James Lovelock in the late 1960s. At the dawn of the Space Age, he was a member of a team at NASA JPL investigating possible experiments to determine whether planets like Venus and Mars could harbor life. Lovelock reasoned that any prospective extraterrestrial planetary biosphere would require a fluid medium, water or air, or both, for the transport of nutrients and discharge of waste. As a consequence, the fluid medium would display a compositional mixture strikingly out of chemical equilibrium. As a matter of fact, this is the case for Earth's atmosphere. Take, for instance, the simultaneous presence of oxygen and methane. In the presence of sunlight, these two gases would react chemically and turn into carbon dioxide and water vapor. Methane should be almost entirely depleted within decades. Yet its concentration in the atmosphere is constant and, as analysis of ice core samples reveals, it has been present for millions of years. Even more captivating is the fact that to preserve this state, around 500 million tons of methane must be being released into the atmosphere annually. And because methane reacts with oxygen, there must also be a replenishment of the oxygen that is lost in the conversion of methane. The same goes for nitrogen, which forms some 78% of the atmosphere. As oceans cover 70% of the planet's surface, chemistry dictates that nitrogen should exist mostly in the stable form of the nitrate ion dissolved in sea water. Yet it is mostly present in the gaseous state in the atmosphere. In his book *Gaia: A New Look at Life on Earth*, Lovelock wrote: "Our results convinced us that the only feasible explanation of Earth's highly improbable atmosphere was that it was being manipulated on a day-to-day basis from the surface and that the manipulator was life itself. The significant decrease in entropy – or, as a chemist would put it, the persistent state of disequilibrium among the atmospheric gases – was on its own clear proof of life's activity."

Life therefore dynamically regulates Earth's atmospheric composition into a steady state. Furthermore, life acts to ensure the planet continues to offer an environment that favors its preservation and flourishment. For instance, the atmospheric mixture of 78% nitrogen and 21% oxygen prevents an outbreak of fire from rapidly spreading across the entire planet. With just a little bit less nitrogen or a little bit more oxygen, even a campfire would pose a severe risk! Any less oxygen, and most of the biosphere would rapidly suffocate, creating a mostly barren world. Thermoregulation is another feature of the biosphere. Our parent star has increased its output by at least 25% since the dawn of life around 3.5 billion years ago. Yet, ice core samples prove that the temperature of the planet has remained relatively constant throughout that time at a level favorable for life. This is potent evidence of how life regulates Earth's climate on a global scale, to establish and maintain conditions for its own survival. Since Lovelock's first peer-reviewed paper on the subject in 1968,[7] the Gaia hypothesis has attracted ever more attention and has been developed into an even more comprehensive framework that defines Gaia as "a superorganism composed of all life tightly coupled with the air, the ocean, and the surface rocks".[8]

In his book *The Vanishing Face of Gaia*, Lovelock says, "The disastrous mistake of 20th-century science was to assume that all we need to know about the climate can come from modelling the physics and chemistry of the air in ever more powerful computers, and then assuming that the biosphere merely responds passively to change instead of realizing it was in the driving seat … Real observations and measurements falsify the 21st-century view of the Earth as a passive resource. … The natural world outside our farms and cities is not there as

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[7] The paper 'Planetary Atmosphere: Compositional and other changes associated with the presence of Life' was published in the Proceeding of the American Astronautical Society in 1968.

[8] As Mars and Venus lack any surface liquid body of water, the only medium any potential life can exploit for raw material transport and waste disposal is the atmosphere. Extensive surveys of both planet's atmosphere have shown that their composition are near chemical equilibrium. Consequently, based on the Gaia hypothesis, neither planet bears life.

decoration but serves to regulate the chemistry and climate of the Earth, and the ecosystems are the organs of Gaia that enable her to maintain our planet habitable." Despite our invasive way of living, "Gaia has long been resisting our interventions through negative feedback; opposing the way we change the air with greenhouse gases and take away its natural forest cover for farmland."

In the new age of the Anthropocene, this self-regulating mechanism, which also provides a comfortable environment for the human species, has come under serious threat. However, and perhaps unexpectedly, Gaia will always be the winner. As Lovelock continues, "It is often wrongly assumed that life has simply adapted to the material environment, whatever it was at that time; in reality life is much more enterprising. When confronted with an unfavorable environment it can adapt, but if that is not sufficient to achieve stability it can also change the environment. We are doing this now … and the Earth system seems to be giving up its struggle and is preparing to flee to a safer place, a hot state with a stable climate … A look at the Earth's climate history tell us that in such hot states Gaia can still self-regulate and survive with a diminished biosphere … This is how Gaia keeps an habitable planet: species that improve habitability flourish, and those that foul the environment are set back or go extinct." Humans are in the latter group.

And we are certainly aware of it, given that in recent years we have been witnessing a growing number of "green" activist movements that place emphasis on sustainability and caring for the environment in any infrastructure project, be that small or large. As noted earlier, access to and manipulation of resources are among the activities that are primarily responsible for the mistreatment of Gaia and the imperilment of our own survival. There are many suggestions for how we might reverse this trend, or mitigate the issue.

One reasonable approach would be to acquire resources and transform them into commodities in a place where the concept of environmental pollution simply does not apply. Could such a setting exist? If we want to attempt to mitigate our harm to Earth's biosphere, the only reasonable location where resource extraction and manufacturing of goods could take place would be in a territory that is lifeless.

Space is such a domain. As far as we are aware, nothing lives in space. In fact, just about any physical property of space is inimical to life in the absence of extraordinary precautions by means of sophisticated technology. The idea of exploiting the resources of space and of producing goods in orbit is not new. Even before Apollo 11 landed on the Moon, NASA and many visionary engineers were proposing a space program that would just do that. In the 1970s and 1980s several notable studies were undertaken to investigate such possibilities; reports were published, conferences were held, and timid experiments of on-orbit manufacturing undertaken. But no serious consideration was ever given to the possibility that space might not only be a venue for discovery but also a useful resource for the betterment of Earth and Gaia.

The time has now come to revisit this idea, particularly now that we have come to realize the damage we have already inflicted on our planet. I firmly believe that space-related activities can, and should, be part of the list of solutions we are implementing to preserve and repair the environment. Space-related activities cannot, and should not, be merely the way that a country parades its technological prowess or achieves military supremacy, or even how it satisfies its thirst for pure knowledge.

Recalling what O'Neill wrote, space-related activities must satisfy humanitarian needs such as "finding high-quality living space for a world population" and providing "unlimited new material sources, available without stealing or killing or polluting". A clean environment, or to put it another way a biosphere that is not burdened beyond its regenerative capabilities, would undoubtedly assist in providing a high-quality living space. Jeff Bezos, Amazon's CEO, is a strong advocate for exploiting the resources of space and transferring heavy manufacturing industries into space. He too is a follower of O'Neill's vision. As often happens, visionaries are regarded as oddities who should not be taken too seriously. We live in a fast-paced word that seeks instant gratification. This has made us almost incapable of following a long-term plan that might not come into fruition until after we are long gone. But if we want to preserve the magnificence of our planet's biosphere and live in harmony with its countless ecosystems, we should implement as many options as possible, one of which is space resource mining and the establishment of in-space manufacturing industries to augment (and later replace) their terrestrial counterparts.

This is the theme that we will develop throughout the next chapters. Rest assured that it is not my intention to offer such space-related activities as a panacea to solve all our environmental crises. The problem is sufficiently multifaceted to require a diverse mix of solutions. But I am convinced that space-related activities have the potential to be a significant part of a blend of solutions, each targeted towards one or more specific issues. Chapter by chapter, we will see how this capability can first be expressed, then transformed into reality.

Chapter 2 will focus on the resources that space has to offer, and summarize what decades of observations and sample analyses have told us about the compositions of the Moon and asteroids.

In Chapters 3 and 4 we will explore methods suggested for mining and processing such resources, to transform them to feedstock materials suitable for the manufacturing of highly valuable products in space. Although resource mining is a practice almost as old as humankind, we will appreciate how the environment of space and extraterrestrial surfaces can either hinder or promote the extraction and processing of raw materials.

Chapters 5 and 6 will show us how manufacturing can be undertaken both in orbital space and on celestial bodies. As stated earlier, industrial production is another crucial player in the alteration of the planetary biosphere. Space-based manufacturing can ease some of the stress that we have been placing on the terrestrial environment.

Chapter 7 will look at several technologies that are already available to us or are in development that can help us to jump-start a space-based manufacturing infrastructure capable of partially replacing what we have on Earth.

In Chapter 8 we will wrap up by highlighting how it is not beyond our capabilities to implement a space program that can deliver genuine benefits to humankind, and will consider some additional rewards that might accrue from space-based manufacturing.

Let us build a space program worth undertaking!

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IMAGE LINKS

Figure 1.1: The International Space Station. Operating an Outpost in the New Frontier. (2018). NASA, p.19.

Figure 1.2: https://mars.nasa.gov/resources/3650/curiositys-sky-crane-maneuver-artists-concept/

Figure 1.3: https://settlement.arc.nasa.gov/teacher/70sArt/art.html

Figure 1.4: NASA Spinoff 2017. (2018). [pdf] NASA. Available at: https://spinoff.nasa.gov/Spinoff2017/index.html [Accessed 24 Jul. 2019].

Figure 1.5: https://www.overshootday.org/newsroom/past-earth-overshoot-days/

2

Extraterrestrial Resources and Where to Find Them

RESOURCES: EARTH VERSUS SPACE

“Resource” is a term widely applied to a variety of fields ranging from business to economics to geology. Before we explore the materials available in the Solar System, we had best clarify what we mean by “resource” in this context.

First, we have to recall what a mineral is. A simple definition is that a mineral is a compound of one or more chemical elements, usually in a crystalline structure, and is the result of natural unanimated processes rather than ones that are related to life. Some 3,000 minerals have been identified dispersed throughout Earth’s crust. But there are regions in which the concentration of one or more minerals is increased by several orders of magnitude relative to the average, and for which geological surveys have ascertained a potential economic benefit that might derive from the extraction and exploitation of such mineral(s). These areas are defined as *mineral reserves or mineral resources*. However, often not all of a mineral resource is up for mining, as the conditions of the region might be too challenging or costly to permit profitable extraction. Aspects to consider are the available extraction technology, the logistics infrastructure required to deliver resource to a processing plant, market demand for that particular resource, environmental concerns arising from disturbing the area that is to be mined, and government control. Those sectors of a mineral reserve for which a mining company can initiate a profitable extraction operation are defined as *ores* or *ore reserves*.[1] Hence an ore is a subset of a mineral resource. As the demonstrated economic profit is a cardinal parameter that regulates the establishment of an ore reserve, it

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[1] For certain reserve types other terms have been adopted such as “seams” for coal and “wells” for crude oil.

D. Sivolella, *Space Mining and Manufacturing*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-30881-0_2

follows that the size and number of ores accredited to a given reserve can change over time. As the demand for materials increases, areas of a mineral reserve that had previously been judged to be either unprofitable or not feasible for mining can attain ore reserve status and be exploited. A good case in point is the extraction of oil and natural gas. While in the past, wells situated in deep oceanic waters were deemed too challenging to reach and thus not worth exploiting, nowadays more and more oil rigs are being positioned over such areas and there is a move towards waters nearer the arctic regions.

Although the above definitions are applicable to any celestial body in the Solar System, there is a substantial difference in the nature of the reserves and ores found on Earth and those currently estimated for the Moon and asteroids. On Earth, mineral reserves are often the result of active geological processes significantly influenced by the presence of liquid water and atmospheric oxygen. You might remember from science classes that Earth's crust is actually a global system or jig-saw puzzle of continental and oceanic plates that are slowly migrating on top of a layer of silicate rock that has the properties of a viscous fluid. In a subduction zone, where one plate slides beneath another, silicate hydrate rocks[2] are forced down towards the mantle below the crust, where high pressure and temperature liberate the water from the rock and produce a supercritical hot fluid. In this state, water is neither a liquid nor a gas. It can diffuse through a solid like a gas and dissolve materials like a liquid. In these conditions, the supercritical hot water is so reactive that it can dissolve several kinds of minerals and metal ions – even those that would not normally be soluble in water, such as gold and silver. This water is returned to the surface via volcanoes, geysers, and hot springs, where it cools and releases the dissolved minerals and metals. These then create high-grade mineral deposits. In fact, it is not by chance that ores usually occur where subduction took place in the remote past. For example, the Mediterranean region, lying between the African and European continents where an ancient ocean is being squeezed out, has seen much subduction and volcanism. And the famed California gold rush of 1849 was triggered by the discovery of gold ores left over by the hydrothermal processes that occurred when central California was at the edge of an ancient continent.

In certain instances, the generation of mineral reserves and ores can be assisted by bacteria and other life forms, because they can enhance the solubility of ions and thus speed up the inorganic process of ore formation. In some other cases, biological processes are the principal factor in the development of a given resource, such as the production of hydrocarbons and coal. The formation of an ore does not necessarily require high-pressure water. In fact, evaporation of a body of water can leave on the ground a mineral-rich residue. A typical example in this regard is the Bolivian Salar de Uyuni region, whose salt flats have the planet's largest reserve of lithium. Another process that does not require supercritical water is the dissolution of metal elements into molten magma and later fractional distillation

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[2] These are rocks whose chemical compounds include water as one of their constituents.

and crystallization. In this case, a crystallizing mineral settles within the melt if its density is greater than the melt. As the melt cools, it creates successive layers of crystals in complex, layered formations called stratiform deposits.

On the Moon and asteroids, where liquid water and active tectonic geology have not played a role, this entire realm of aqueous geochemistry never occurred. What is more, the lack of oxygen and life prevented oxidation and denied the role of biology in the formation of ores. Thus when it comes to resources and ores on extraterrestrial bodies, we cannot expect there to be certain areas with elevated concentrations of a given element or mineral. An exception in the case of the Moon, however, might be stratiform deposits created by fractional distillation when that body had an ocean of magma that slowly crystallized.

Generally speaking therefore, resources are expected to be widely spread across the surface and depth of the Moon's crust, and to be thoroughly dispersed within an asteroid. As we shall see below, this uniformity might ease our mining of the Moon and asteroids.

THE ORIGIN OF THE MOON

How did the Moon originate? Throughout history, speculations on how our natural satellite came to exist have abounded. If we restrict ourselves to modern conjectures, we can start with Charles Darwin's son, Sir George Howard Darwin, who postulated in 1878 that the Moon must have formed through a planetary-scale process of fission in which the Moon was detached from Earth. He based this rationale on the fact that the time taken by the Moon to make orbit of Earth is slowly increasing. In accordance with Kepler's third law of astrodynamics, this implies that the Moon is progressively moving away from Earth.[3] Thus, he reasoned, the Moon must once have been much closer. Logically, therefore, the Moon and Earth must have started as a single entity. A fellow scientist, Osmond Fisher, had earlier suggested that the vast Pacific Ocean was the scar left by the separation of the Moon.

But ideas for how nature behaves stand or fail by their mathematics. The 'fission hypothesis' failed the test known as the Roche limit. Named after French astronomer Edouard Roche, this is an important parameter used in modern

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[3] The increasing of the Moon's orbital period is related to the decrease in Earth's rotation time (the length of a day) due to dissipation of tidal energy as a result of the friction of the moving mass of water with the underlying crust (sea bottom). As the angular momentum of the Earth-Moon system must remain constant, it follows that as Earth's day diminishes, the Moon has to move slowly outward. To better understand, liken the Earth-Moon system to an ice-skater pirouetting: by opening or closing their arms the skater can alter the spin rate because the angular moment is conserved.

astronomy to study planetary systems that possess rings, such as Saturn. It applies to two or more bodies of significantly different masses and, stated in simple terms, the limit represents the minimum distance at which a smaller body (e.g., a natural satellite) can survive the gravitational attraction of the larger body in the system (e.g., a planet) and remain as a distinct body held together by its own gravity. At a shorter distance, the tidal forces exerted by the larger body overwhelm the tensile strength of the smaller body, which is then ripped apart to produce a cloud of debris that can then disperse and become a spectacular ring.[4] The Roche limit is approximately equal to two planetary radii. For Earth the limiting separation is 12,000 km. Consequently, even though the Moon must have been much closer to Earth in the remote past, it could not have existed as a body held together by self-gravitation inside that distance.[5] Therefore the presence of the Roche limit lent credit to the 'co-accretion hypothesis' proposed by the French astronomer and mathematician Pierre-Simon Laplace, whereby Earth and the Moon were created simultaneously in the same region of the Solar System, with the greater gravity of Earth drawing the Moon into orbit.

At the start of the 20th century, a number of retrograde satellites were discovered orbiting Jupiter and Saturn. In astronomy, retrograde motion is defined as an orbit in the opposite direction to the central body's rotation. Thus, if a planet is rotating in a clockwise direction (by convention we view such systems from above), a retrograde satellite will be going counter-clockwise. As planets and their natural satellites were formed from a single accretion disk of particles and gas, the orbital motion of a moon will match the direction of rotation of a planet.[6] A retrograde moon can only have originated somewhere else. The discovery of retrograde satellites gave credibility to the 'capture hypothesis' in which the Moon was formed independently, elsewhere in the Solar System, and at some time in the remote past it came close enough to Earth to be captured by it.

It was hoped that the origin of the Moon would be settled by the Apollo program, but the returned samples revealed a complex mineralogy, the result of a past active

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[4] Indeed, all but the two outermost of Saturn's rings are within its Roche limit (or radius). The E-ring is the result of geysers emanating from the moon Enceladus's south pole. They issue microscopic particles of water ice with silicates, carbon dioxide, and ammonia. The Phoebe ring is the largest being some 7,000 times larger than Saturn itself. Discovered only in 2009 by observations using the WISE infrared telescope, it is believed to consist of grain of dust blasted off Phoebe's surface by cosmic impacts.

[5] Why is an artificial satellite orbiting at an altitude of just a few hundred kilometres not ripped to pieces by Earth's gravity? The Roche limit applies only to bodies that are held together by gravitation causing unconnected particles to coalesce. Artificial satellites are assembled by means of mechanical joints and the bodies of astronauts are held together by chemical bonds.

[6] A notable exception is Uranus. Its axis of rotation is tilted by 97.7 degrees so that the equator is nearly at a right angle to the plane of its orbit. Effectively, the planet is rolling along its orbital path. Such an extreme tilt is most likely the aftermath of a collision with an Earth-sized planet.

geology, and rearrangement of material by meteorite bombardment which in some extreme cases extensively remodeled and mixed the superficial crust and underlying mantle material. In truth, the debate about the origin of the Moon might never find a definitive result. In recent years, analysis of the Apollo samples and mapping of the surface have yielded a new theory that merges the previously discussed hypotheses. This 'planetesimal impact hypothesis' postulates that a Mars-sized object might have struck the proto-Earth, expelling a vast amount of material (fission hypothesis) that then condensed into orbit (co-accretion hypothesis) and incorporated a lot of material left over from the impactor (capture hypothesis). Although the true origin might have been more complex and dynamic, the planetesimal impact hypothesis does resolve dilemmas in dynamics, chemistry, and geophysics which conflict with the individual classical hypotheses. For instance, it explains the Moon's relative lack of iron, as the iron-rich core of the impactor could have merged with that of Earth. It also accounts for the tilt of the Moon's orbital plane and the greater amount of angular momentum possessed by the Earth-Moon system as a result of the impactor striking Earth at an angle and increasing its angular momentum.

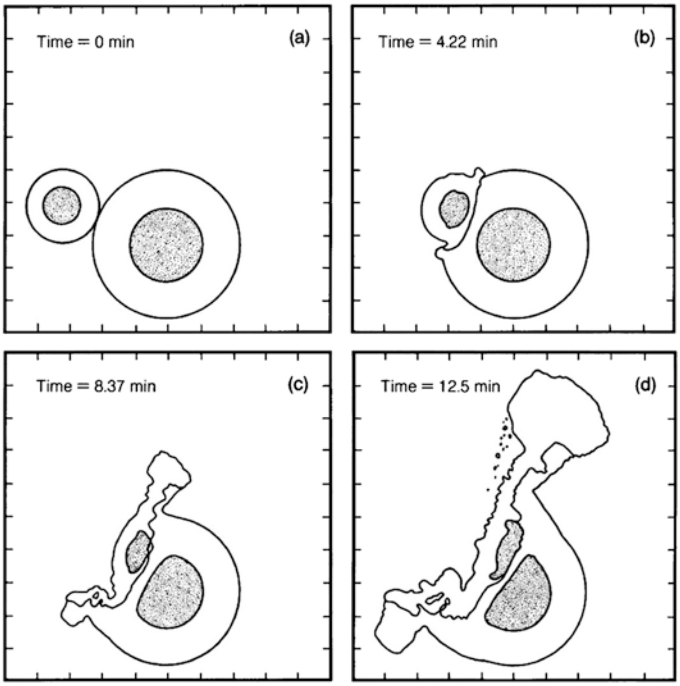

Figure 2.1 A computer simulation showing 12.5 minutes in the duration of a hypothetical collision between a Mars-sized planet and the proto-Earth. The dotted circles at the center of each planet represent their metallic cores, which are surrounded by silicate mantles. In this illustrated hypothesis the jet of silicate material shown in the final frame will become a large part of the Moon. The metallic parts of both bodies will coalesce inside Earth. The Moon ends up with little or no metallic core. This fits our present knowledge of our natural satellite.

MOON TOPOGRAPHY 101

Although thousands of pages have been written both at popular science and technical levels detailing every single feature visible on the Moon, three of its most prominent provinces are discernible to the naked eye, namely its basins, maria, and highlands.

We believe that in the early stages of the Moon's formation the heat released by the process of accretion turned the outer surface into a global magma ocean that was 200-400 km deep. As it cooled, it solidified to create a thick, rigid, immobile crust which was later extensively transformed by volcanism, by impacts and, to a lesser extent, by tidal forces.

The basins are the single largest features on the Moon and usually include at least one ring of mountains. Only impacts by massive asteroids possesses enough kinetic energy to deform the crust on such a tremendous scale. Basins differ from craters in the size of the excavation. It is arbitrary, but craters with diameters that exceed 300 km are basins. The most prominent ones are the Orientale Basin, the Imbrium Basin, and the South Pole-Aitken Basin.

There are large dark areas on the Moon that the Italian renaissance astronomer Galileo Galilei referred to as 'mare', the Latin term for 'sea'.[7] We now know there are no bodies of water on the Moon. Although the terms basin and mare are widely used interchangeably, they are in fact two distinct features. While the basins have an impact origin, the maria are the result of volcanism. Once a basin had been formed, lava could later well up through deep cracks in the floor and fill the cavity to create the relatively flat mare plains. Not all basins are filled with lava. The surface of the Orientale Basin on the Moon's far side is exposed. In fact, only a few basins on that side of the Moon have been filled.[8] For basins that have been filled with lava, their mare shares the name of the basin. Thus, Mare Imbrium resides within the Imbrium Basin. Photogeology and spectral analysis have revealed that in many cases a mare is the result of many lava extrusions over a lengthy period of time. Some 17% of the nearside of the Moon is covered with lava. An additional 13% has lava concealed by ejecta from impacts in nearby locations. These covered maria are called cryptomaria ('crypto' means 'concealed').

The mare material originated in the mantle. Even though the magma ocean had cooled to form a solid crust, internal heating caused by the decaying of radioactives such as uranium and thorium produced localized melting of the mantle. After rising through networks of fissures, these lavas poured out onto the surface. In the presence of vacuum the lava quickly crystalized. However, they were richer in iron and poorer in aluminum and silicon than most lavas on Earth. Having a low viscosity (meaning that they were relatively fluid) they could cover vast areas prior to solidification. A number of samples returned by the Apollo astronauts also revealed the presence of pyroclastic deposits, otherwise known in common parlance as volcanic ash. This was caused by gases within the magma. As the lava rose through fissures to the surface, the decompressed gas expanded to create explosive fountains of droplets of

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[7] The plural of mare is maria (seas).

[8] Most likely because of the thicker crust.

molten material. A lava that cools slowly forms crystals but one that is instantly frozen forms glass. The fountains spewed out glassy beads. In the low gravity of the Moon, these beads were able to travel to a considerable distance from the volcanic vent. Models of lunar volcanism have determined that to permit the high eruption rate of at least 1 m/s needed to create the observed lava flows, the fissures could be no wider than 10 meters. This is not to say that the volcanism occurred in the immediate aftermath of the excavation of a basin. For instance, there is evidence that the Imbrium Basin was created some 3.9 billion years ago and there was a hiatus of some 600 million years before the material that now forms Mare Imbrium was erupted. Generally speaking, the mare material is what geologists called a partial melt, which is composed of those minerals that melt most easily at mantle pressure. Hence a partial melt does not have the same composition as the mantle from which it came. However, it is chemically complementary to the residual unmelted mantle material left behind. Thus, based on the partial melt constituents and applying thermodynamic principles involved in the equilibrium of partial melting, the bulk

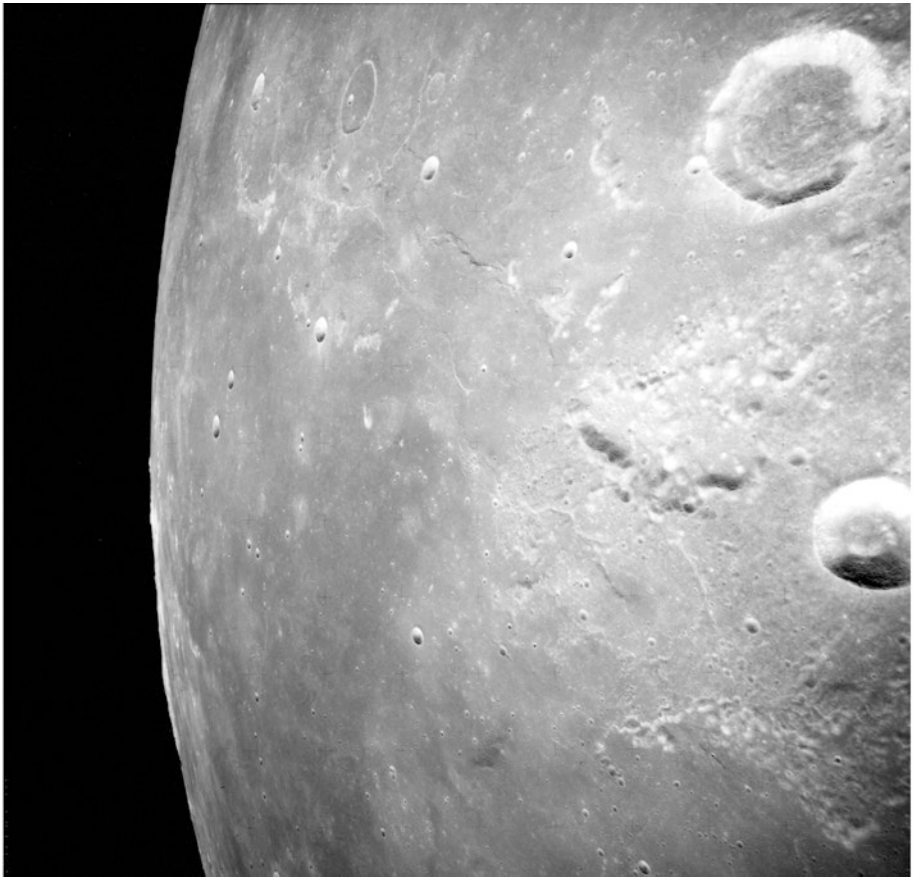

Figure 2.2 The Sea of Tranquility (Mare Tranquillitatis) on which the Apollo 11 mission landed, as seen by the Apollo 17 astronauts. Clearly evident is the characteristic flatness of a lunar maria, interrupted occasionally by a crater.

composition of the mantle can be calculated. The mineralogy of the maria material is dominated by a combination of magnesium (Mg), iron (Fe), silicon (Si), calcium (Ca), aluminum (Al) and titanium (Ti). In other words, they are basaltic. Lunar maria are usually classified based on their titanium content, which is incorporated in a mineral compound of iron, titanium and oxygen called ilmenite ($FeTiO_3$).

The highland regions could easily be mistaken for mountain ranges but, given the absence of active plate tectonics such as dominates on Earth, the highlands represent those areas of the Moon's surface that did not suffer impacts on the scale that created basins. The highland regions are as much as 16 km higher in elevation than the floors of the deepest basins. The mountain ranges which border basins are a direct result of crustal deformation in adjusting to the mechanical stress as the basin was excavated. Unlike terrestrial mountain ranges, which were thrust up over considerable periods by tectonic forces, the rings associated with the lunar basins were formed essentially instantaneously.

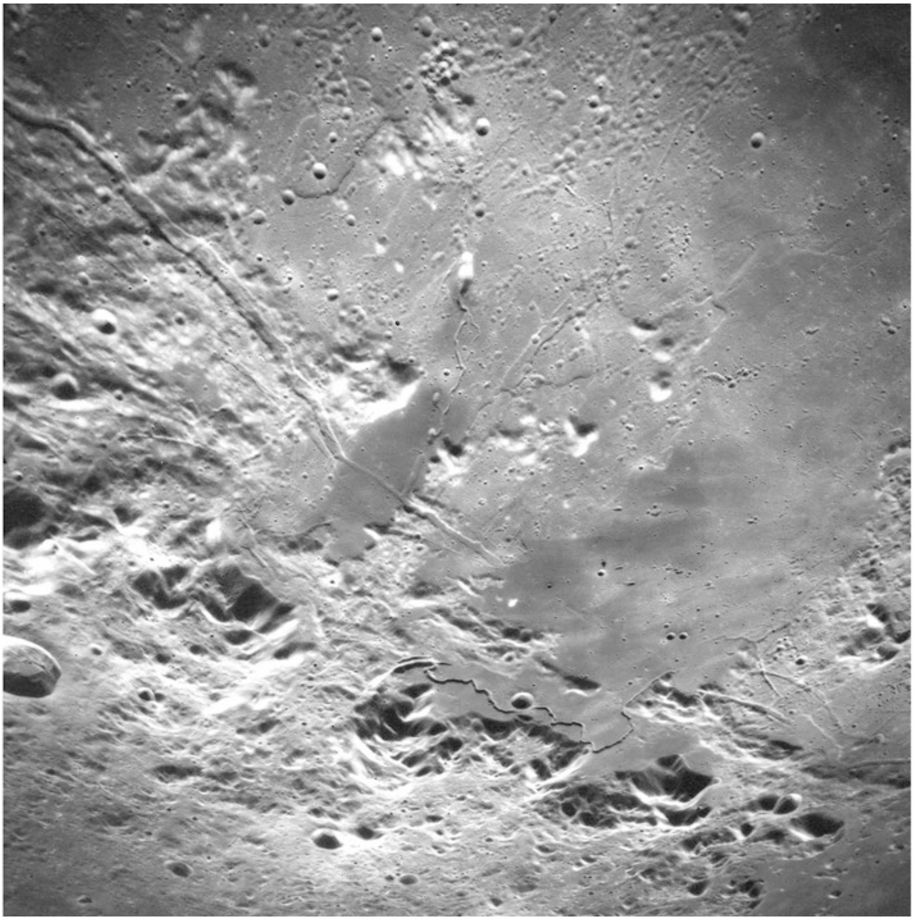

Figure 2.3 The Apennine Mountain Range (Montes Apenninus) as seen by the Apollo 15 astronauts. Mare Imbrium is the flat surface that runs from the center of the image towards the upper left. The difference between a mare plain and the rough terrain of the highlands is straightforward to perceive.

MOON PETROLOGY

All rocks on the Moon's surface have an igneous origin because they were formed by the cooling of molten material (magma) to create rocks composed of interlocking minerals and glass.

We have already seen that the maria are basaltic types of rock along with volcanic ash. The highlands are instead rich in anorthositic rocks that are mainly a formulation of plagioclase feldspar. This is a mineral category characterized by a solid solution[9] of sodium (Na), aluminum (Al), calcium (Ca) and oxygen (O) contained in a silicon framework. In addition to plagioclase feldspar, some highland rocks contain varying amounts of pyroxene and olivine. Avoiding complicated petrological explanations, these are the general names for two groups of silicate-based minerals that display a considerable solid solution with major elements such as calcium, iron, magnesium, and aluminum. In particular, pyroxenes are silicates with one silicon atom for each atom of magnesium, iron, or calcium. Olivines are silicates with two atoms of iron or magnesium per silicon atom. The many ways that these elements can be arranged account for complex families of minerals, each with its own chemical and physical characteristics.

Regardless of the location, the surface of the Moon is covered by a complex layer of regolith up to several meters thick. In the technical literature, it is "fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms on the surface of the land and overlies or covers bedrock". In simple terms you can think of regolith as soil. However, there is a significant difference between the regolith present on Earth and that on the Moon. Terrestrial regolith is the result of the overall action of processes related to oxidation, weathering, and anthropogenic as well as natural activities. On the airless Moon, the regolith is the result of billions of years of asteroid and meteoroid bombardment and superimposition of countless instances of bedrock shattering, pulverization, melting, mixing, and debris dispersal. At the start, any impacts, regardless of the size of the impactor, destroyed the bedrock and exposed fresh crustal material as the target for further bombardment. This enabled a rapid thickening of the regolith layer, but over time only larger (and less frequent) impacts could penetrate through the regolith and attack the underlying bedrock to further thicken the regolith. The smaller (but more frequent) impacts would just rearrange the regolith, consolidating and compacting it in a process named 'gardening'. This process will continue for as long as the Moon

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[9] This is a solid homogenous mixture of one or more substances (denominated solutes) dispersed within the crystalline structure of a solvent (the substance that is capable of dissolving a solute).

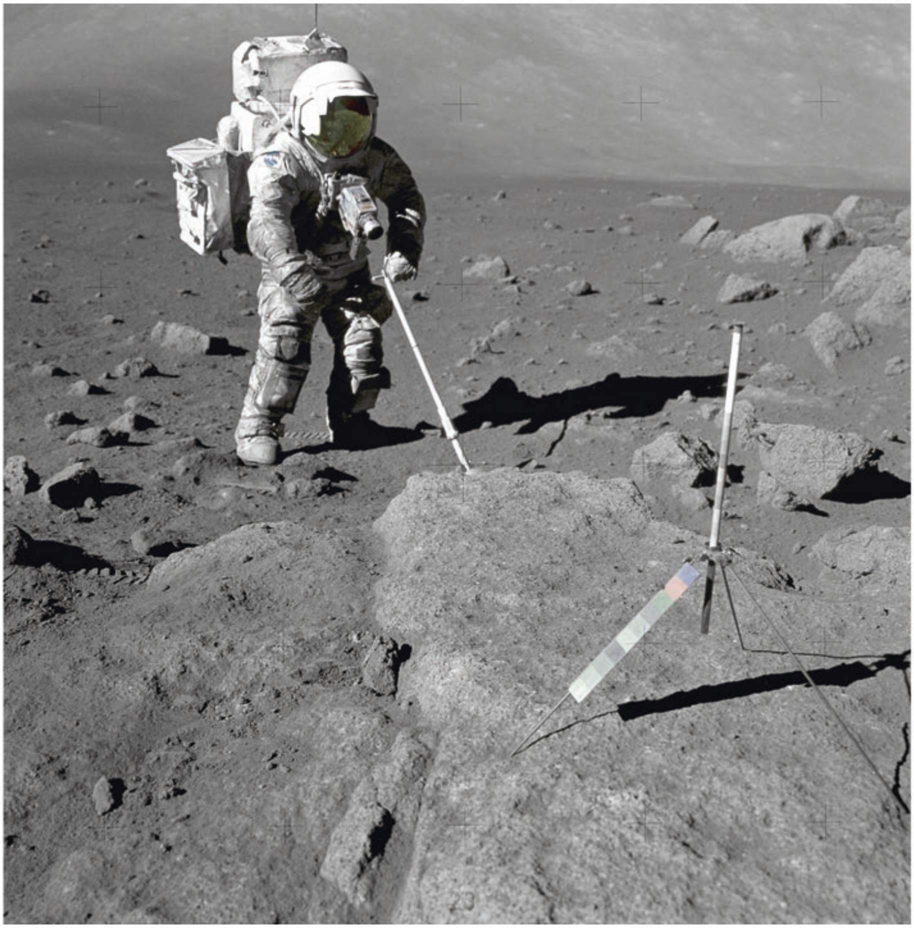

Figure 2.4 Apollo 17's Moonwalker Harrison Schmitt scooping up a lunar sample. Notice that what started out as an immaculate white space suit is by this point almost entirely covered in dark lunar regolith.

exists.[10] According to measurements and models, the regolith is some 10-20 meters thick in the ancient highland regions and only between 4-5 meters thick on the maria.

One distinctive feature of the lunar regolith is a kind of rock named 'breccia'. In the aftermath of an impact, the intense heat released by the collision serves to weld together shattered lunar bedrock, clots of impact-melted rocks, and glass fragments. For this reason, they are known as polymict breccias. Depending on

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[10] Regolith by meteorite and solar wind bombardment is not peculiar to the Moon, it takes place on any airless celestial body such as the asteroids.

the time allowed for the melt to cool down, breccias are characterized by a glassy or crystalline spatial arrangement of finely grained material which penetrates the interstices left by larger fragments.[11] Their composition is either similar to the soil of the area in which the impact occurred, or a mix of that soil with the impactor. Given the extensive period during which the Moon suffered severe meteoroid bombardments, the vast majority of breccias contains traces of previous generations of breccias. More challenging to find are the monomict breccias which contain material from a single type of rock; in other words, highly crushed samples of a single lunar bedrock type that survived the massive bombardment without contamination, mixing, or other significant chemical alteration. For this reason, monomict breccias are important samples of the makeup of the lunar crust.

Another important constituent of lunar regolith is the soil that consists of particles at the sub-centimeter scale. Although the terms lunar regolith and lunar soil are widely used interchangeably, the soil is a constituent of the regolith. The regolith also contains larger particles, such as breccias, whose sizes range from pebbles to large rocks. The gardening process then compacts everything together. In fact, while the uppermost few centimeters are powdery (as is readily discernible in the pictures of the boot prints of the Apollo astronauts), at a depth of 30 centimeters the regolith is highly compacted. Indeed, the Apollo samples revealed that the soil contributes the bulk of the regolith and is composed of five distinct particle types: mineral fragments, pristine crystalline rock fragments, breccia fragments, glasses of various type, and agglutinates. An agglutinate is another product of the impact process. It is sometimes also called fused soil. Agglutinates are aggregates of fine soil particles such as dust grains, glasses and even other agglutinates, which were glued together by the silica in the bedrock that melted during the impact. Because of the rapid cooling undertaken by the melt in the vacuum of space, agglutinates generally possess an amorphous glassy structure. On average, 25-30% of the soil is agglutinates, but depending on the location it can vary from as low as 5% to about 65%. Because agglutinates are constantly being formed by even the tiniest of micrometeorite impacts, their abundance increases over time.

LUNAR RESOURCES

The assortment of elements that we can reasonably expect to dig out of the Moon's surface is summarized in Figure 2.5. It is the result of years of spacecraft observations and an exhaustive analysis of the rock samples collected by the Apollo astronauts.

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[11] A glassy matrix is produced during rapid cooling so that a definite spatial highly organized arrangement of the breccia's constituents cannot be established. If enough time is provided, the constituents have the opportunity to settle into an organized structure known as a crystal.

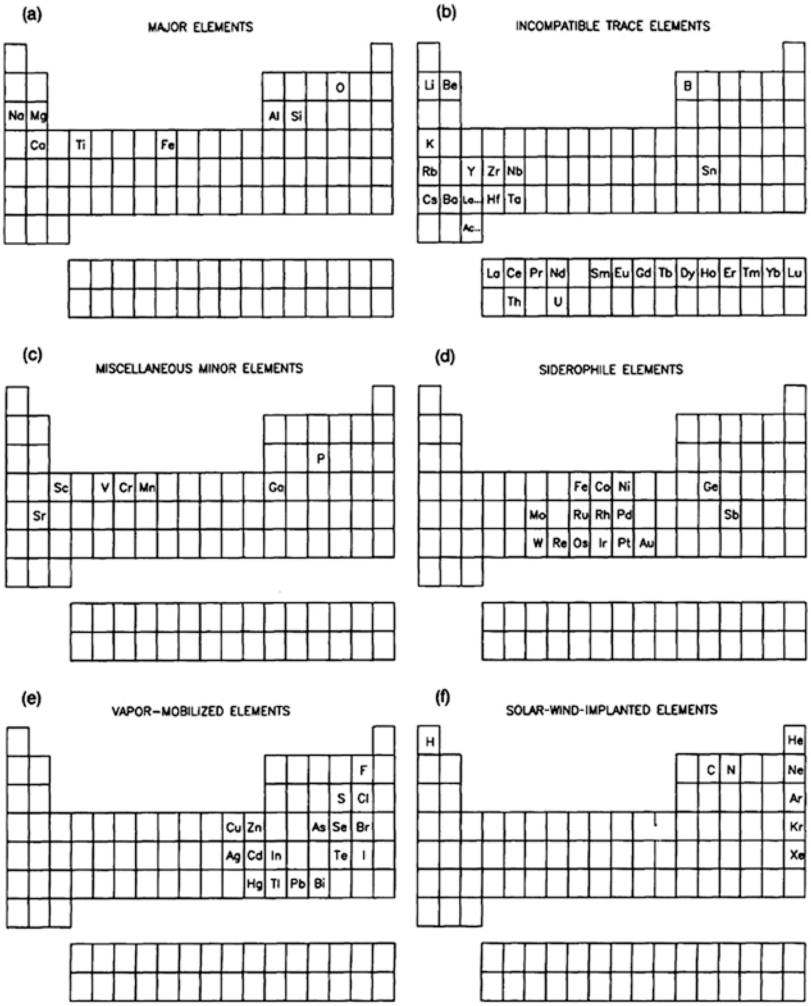

Figure 2.5 Diagram of the Periodic Table of the Elements showing the variety of elements that are available on the surface of the Moon.

The elements that make up the bulk of the common lunar material, referred to as the major elements, are oxygen (O), sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), calcium (Ca), titanium (Ti) and iron (Fe). For instance, in terms of their weight-percentage 45% is oxygen, 21% is silicon, 13% is aluminum (although for the maria it is only 5%), 10% is calcium (8% in the maria), 6% is iron (but as much as 15% in the maria), and 5.5% is magnesium. Titanium and sodium each contribute a fraction of 1% in the highlands, but the average titanium concentration exceeds 1% and may be as high as 5% in the maria. Despite the Moon being utterly airless, the most abundant of all of the major elements is oxygen. This arises because oxygen is found trapped within minerals that are composed of the other major elements, hence it is chemically bound to those elements. However, such oxygen-laden compounds are not simple oxides. Rather they are elaborate mixtures of silicate, oxides, and even glasses produced when impacts melted rocks. Both highland and mare rocks contain plagioclase feldspar, which is a solid solution consisting mainly of two components, anorthite ($CaAl_2Si_2O_8$) and albite ($NaAlSi_3O_8$), with the former being dominant. As its chemical formula implies, plagioclase accounts for nearly all of the aluminum in the crust. The proportion of plagioclase in the highlands is greater than that in the maria, which is consistent with the greater concentrations of aluminum detected by orbital remote sensing in the highlands and observed in the analyses of such samples. That higher proportion of plagioclase, which is white, also helps to explain the light tone of the highlands, in contrast to the darker maria where the predominant minerals are pyroxene and olivine. Pyroxenes occur in two general varieties, high-Ca and low-Ca, both of which are a solid solution of $Ca_2Si_2O_6$, $Mg_2Si_2O_6$, and $Fe_2Si_2O_6$. Olivine is a solid solution of Mg_2SiO_4 and Fe_2SiO_4. The maria were also found to be rich in ilmenite ($FeTiO_3$), which is a carrier of titanium and iron, plus other minerals related to titanium.

As discussed at the beginning of this chapter, it is almost certain that the bulk raw material for any lunar resource will be a complicated mixture of rocks, minerals, and glasses. In fact, such polymict materials comprise most of the samples collected by the Apollo crews and the Soviet Luna 16, 20 and 24 unmanned landers.

Figure 2.5 also shows a subset defined as ‘incompatible trace elements’ that cannot easily be accommodated within the crystalline lattice structures created by the major elements. A particular concentration of trace elements is the so-called KREEP, this being an acronym that represents the peculiar chemical composition for a compound rich in phosphate (K), Rare Earth Elements (REE), and phosphorus (P). Generally speaking, it is believed that concentrations of incompatible trace elements occurred when the magma ocean started to cool and the major elements began to crystallize. The elements that were lighter than the magma rose to the surface, eventually to form the crust (now represented by the highlands). Over time, as the magma cooled, the incompatibles became ever more concentrated in the remaining magma. Eventually, they emerged when lava poured out onto the floors of the basins. As a matter of fact, the spectroscopic investigation of the lunar crust performed by the Lunar Prospector orbiter during 1998–1999 revealed the main reservoirs of KREEP-laden rocks to be the Oceanus Procellarum and Mare Imbrium. Furthermore, rocks rich in KREEP also show concentrations of uranium and thorium because these elements travel well with the rare earth elements.

Despite the lack of an atmosphere, there are regions on the surface of the Moon that have been demonstrated to contain water ice. These are sites in the polar regions that are permanently in shadow, never exposed to sunlight and hence extremely cold. Water would have been delivered by comets and hydrate-rich asteroids, and created by hydrogen in the solar wind combining with oxygen drawn from iron oxides in the regolith. Many of the water molecules would have escaped to space, but some would have migrated poleward and become trapped in the permanently shadowed terrains. Water has also been found locked within the lattice framework of hydrated minerals outside of the permanent shadows.

ASTEROIDS: THE VERMIN OF THE SOLAR SYSTEM

On January 1, 1801, Giuseppe Piazzi, an Italian Catholic priest, mathematician and astronomer, was observing the sky through the viewfinder of his telescope in Palermo, Sicily, when he spotted a faint object the same color as Jupiter. Although Piazzi was concerned with compiling a new star catalogue, repeated observations on the following nights showed that this faint speck of light was moving on the sky with a constant rate. While Piazzi initially considered it to be a comet, the absence of any cometary behavior and a slow, uniform motion quickly led him to think of it as a planet. Indeed, thanks to the German mathematician and physicist Carl Friedrich Gauss, its orbit was quickly found to lie between that of Mars and Jupiter. This supported the Titius-Bode rule, by which, extending outward from the Sun, each successive planet was at approximately twice the distance of its predecessor.[12] Piazzi's discovery was named after the Roman goddess Ceres.

After a second celestial body was found orbiting between Mars and Jupiter in 1802, this one named Pallas, the Hanover-born British composer and astronomer Frederick William Hershel (who had discovered the planet Uranus in 1781) suggested that this class of celestial objects be known by the general term 'asteroid' (from the Greek word *asteroeides* meaning 'star-like'). This was because all of the known planets showed a disk, and these new objects showed as points in even the most powerful of telescopes, just like stars. By 1850, the term had become a standard label for this class of celestial bodies,[13] and they were being found in alarming numbers. As reported by the Minor Planet Center at the Smithsonian Astrophysical Observatory, the worldwide repository of data for asteroids and other minor bodies of the Solar System, at time of this writing (the summer of 2019), some 794,000 asteroids have been catalogued, and many more will have been discovered by the time you are reading this page.[14] Asteroids have been derided as the "vermin of the skies" because they can interfere with observations. The asteroids that orbit between Mars and Jupiter at heliocentric distances in the

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[12] Named after the astronomers Johann Daniel Titius and Johann Elert Bode, this hypothesis fell rapidly out of consideration after it failed to predict the orbit of Neptune, and was superseded by more scientifically plausible theories of Solar System formation.

[13] With the new definition of a planet adopted by the International Astronomical Union on August 24, 2006, Ceres has become a dwarf planet. However, its association with the asteroid belt still remains.

[14] Check the Minor Planet Center at https://www.minorplanetcenter.net/ and be amazed at how rapidly minor planets (or asteroids) are being discovered.

range 2.1–3.3 astronomical units (AU) constitute the ‘asteroid belt’.[15] It is sometimes called the ‘main asteroid belt’, or simply the ‘main belt’, to distinguish it from other populations.

For example, on August 13, 1898 astronomers discovered 433 Eros, an almost 17-kilometer-long asteroid whose perihelion (the closest point to the Sun) and aphelion (farthest point) are 1.1334 and 1.7825 AU, respectively. Traveling in a region of space between Earth and Mars, Eros is not a member of the asteroid belt. We now know of thousands of asteroids whose orbits indicate they are members of different asteroidal populations. One of the most well-known, even to the general public due to increased media coverage and awareness, is the Near-Earth Asteroid (NEA) population. As their name implies, their main feature is that their orbits lie close to that of Earth. As shown in Figure 2.6, NEAs can be grouped into four subsets depending on the size and position of their orbit relative to Earth’s.

Simulations of the dynamics of the Solar System have shown that the average life of a member of the NEA population is roughly 30 million years; a rather brief period in relation to the Solar System’s 4.5 billion of years. This is due to the high likelihood of a collision with a planet in the inner Solar System,[16] or a gravitational perturbation that results in the asteroid being ejected from the Solar System. The fact that the NEA population is significant means it must be being replenished on an ongoing basis. The asteroid belt has proven to be such a reservoir, with Jupiter’s gravity playing the active role.

In 1957, the American astronomer Daniel Kirkwood found that plotting asteroids in terms of their orbital periods (or mean heliocentric distances) revealed there to be a number of orbital periods in the main belt for which there were no asteroids. Analysis of these ‘gaps’ established that these orbital periods were in resonance with the period of Jupiter’s orbit. For example, the 3:1 Kirkwood gap occurs where an asteroid would complete three orbits for every one by Jupiter. An asteroid wandering into any of these gaps would experience a succession of gravitational perturbations when passing close to Jupiter. Over time, this would drastically alter the orbit of the asteroid. It could be ejected from the Solar System, diverted onto a collision course with either the Sun or Jupiter itself, or end up in a stable orbit in the inner Solar System as a new member of the NEA population.

A main belt asteroid can slip into a Kirkwood gap by: (1) a collision with another asteroid; (2) as an effect of solar radiation pressure impinging on the

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[15] An astronomical unit (AU) is the yardstick for measuring distances within the Solar System. According to a resolution adopted by the International Astronomical Union at their 28th General Assembly on August 31, 2012, one astronomical unit is exactly 149,597,870.700 meters, or almost 150 million kilometers.

[16] Among which there is Earth too! This is why we should not underestimate the likelihood of one of these asteroids impacting our home planet. In fact, it can occur rather frequently without catastrophic consequences, but it is only a matter of time before a really large one strikes a densely inhabited area.

asteroid's surface, known as the Poynting-Robertson effect; (3) the emission of thermal radiation off the asteroid's surface, known as the Yarkovsky effect.

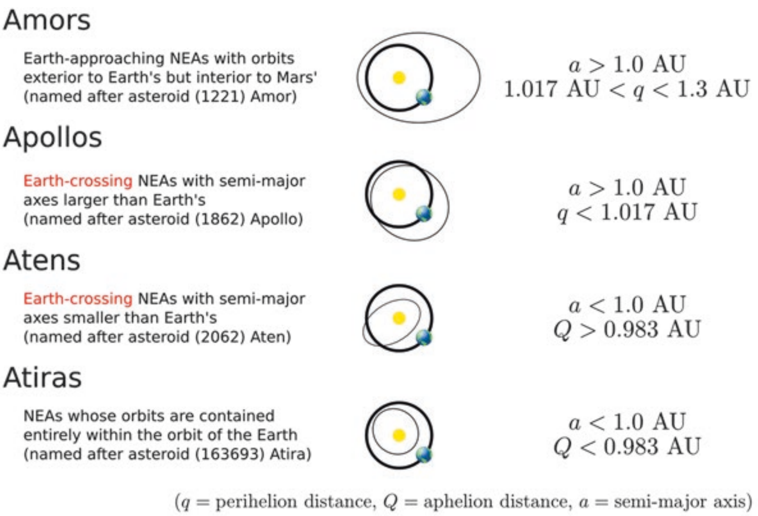

Figure 2.6 The four groups of Near-Earth Asteroids.

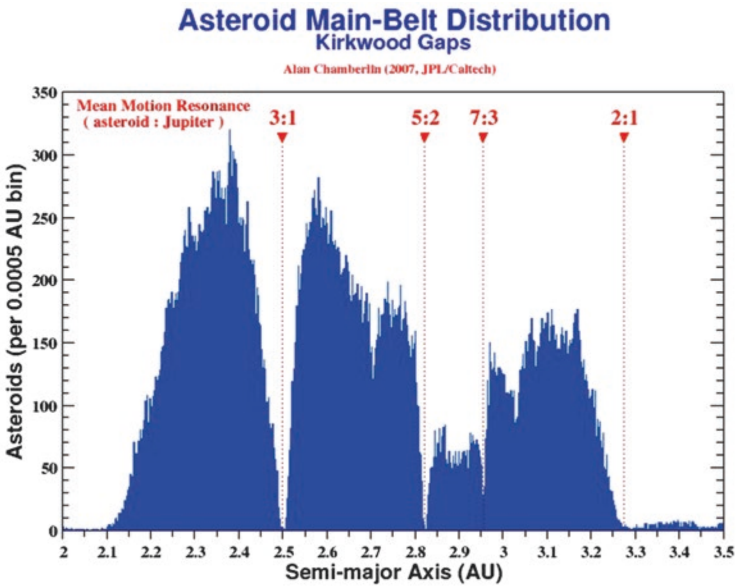

Figure 2.7 The structure of the main asteroid belt. The Kirkwood gaps are represented by the steep valleys for which no asteroid is known. The resonance with the orbital period of Jupiter is highlighted. These regions account for the ongoing replenishment of the population of NEAs.

Simply put, the asteroids are the remnants of the dynamical processes that gave rise to the planets. Following the ignition of the Sun, the cloud of dust and gas surrounding our young star started a new accretion process in which nanoscale grains of dust would coalesce into ever larger lumps. Upon becoming kilometer-sized, these 'planetesimals' could interact with each other via gravitational attraction and collisions. The result was a runaway growth that produced proto-planets several hundreds of kilometers in size. As the accretion process continued, much of the material was incorporated into planets. Some of it was either ejected from the Solar System or dropped into the Sun as a result of interactions with the growing planets. The rest still orbits in the vast open expanses of the Solar System.

In addition to the main belt asteroids and the NEAs, the leftover material from the formation of the Solar System includes the Trans Neptune Objects (TNO), which are divided into two populations as the Kuiper Belt Objects (KBO) and the scattered disk objects (SDO). KBOs are objects with an average heliocentric distance in the range 30-55 AU and they tend to be in almost circular low-inclination orbits that may or may not be in resonance with Neptune. The most well-known member of this class is Pluto. The SDOs are farther out and they follow very eccentric and inclined orbits that do not display any resonance with Neptune.

The outer limit of the Solar System is the spherical Oort Cloud. Named after the Dutch astronomer Jan Oort, this is a widely-scattered swarm of objects that have high eccentricities and random inclinations. It starts far beyond the TNOs and could extend outward for several light-years. Long-period comets are believed to originate from this region of space.

The Trojan asteroids are two clusters of small bodies which travel in the same orbit as Jupiter but occupying the Lagrangian points located 60 degrees ahead of and behind the planet.[17] In fact, this a common arrangement. Uranus and Neptune each have their own clusters of Trojans.

In addition, the Centaur asteroids resemble the NEAs in that their orbits cross those of one or more of the planets of the outer Solar System.

METEORITES 101

If you walk on the icy and snowy surface of Antarctica or the sandy terrain of a desert and you find a rock, usually dark in color, which clearly doesn't belong there, then you have likely found a visitor from space in the form of a meteorite.

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[17] Named after the French mathematician Joseph-Louis Lagrange, a Lagrangian point is a location in space at which the gravitational pull of two large bodies (such as Earth and the Moon) are in equilibrium and hence a third smaller body (such as a spacecraft) will remain in the same position relative to two bigger bodies. Due to geometric considerations, any two-large body system is characterized by five Lagrangian points.

The chances are that you are already familiar with this term, and that you might also be acquainted with the words meteor and meteoroid, but before proceeding with this section we should clarify these terms because they are often incorrectly used as if they were interchangeable.

Simply put, a *meteoroid* is a 'space rock' that can range in size from a dust grain to a small asteroid. They can originate from collisions between asteroids, from the impact of an asteroid with a planet or a moon, or from a comet passing near the Sun. If a space rock is captured by Earth, or any other celestial body that has a significant atmosphere, the hypersonic velocity of atmospheric entry will generate considerable aerodynamic friction which trades kinetic energy for irradiated heating. In association with chemical interactions with the gases of the atmosphere, and ablation of the meteoroidal material, the result is a streak of light in the sky which typically lasts for a fraction of a second. This is a *meteor*. Other popular names are 'shooting stars' or 'falling stars'. Depending on the size, mechanical properties, and composition of the space rock, part of it might survive the atmospheric passage and crash to the ground, perhaps excavating a crater, damaging property, or even injuring people and animals.[18] Any fragment of the space rock found at the impact site is a *meteorite*. If an unusually large space rock such as a small asteroid or cometary nucleus penetrates the atmosphere, the large mass produces a meteor of such a brilliance that is called a *fireball*. According to the American Meteor Society, a fireball is a meteor whose brightness is at least that of the planet Venus in the morning or evening sky; i.e. *very bright*.

If the meteoroid experiences one or multiple explosions during atmospheric entry, each blast will be visible as a flash of light that is much brighter than a fireball. There will be a sonic boom, possibly sufficient to produce serious damage to properties and persons. The light emitted during such an explosive event is called a *bolide* (from the Greek word '*bolis*', which means missile or flash). A recent bolide that received a great deal of media attention was the Chelyabinsk meteor caused by an approximately 20-meter-diameter NEA entering the atmosphere over Russia on February 15, 2013, and exploding over the Chelyabinsk region. Another well-known bolide occurred on the morning of June 30, 1908, near the Stony Tunguska River in Eastern Russian Siberia. The resulting shock waves flattened some 2,000 square kilometers of taiga, destroying thousands of trees. Surprisingly, there were no recorded human casualties. It is still not clear what this object was, but meteoroid size estimates range from a diameter of 60 to 190 meters depending on whether it was a cometary nucleus or a dense asteroid.

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[18] The only recorded instance of a meteorite hitting a person is that of Ann Hodges, who received a deep bruise when a nine-pound meteorite fell through the ceiling of her house on November 30, 1954.

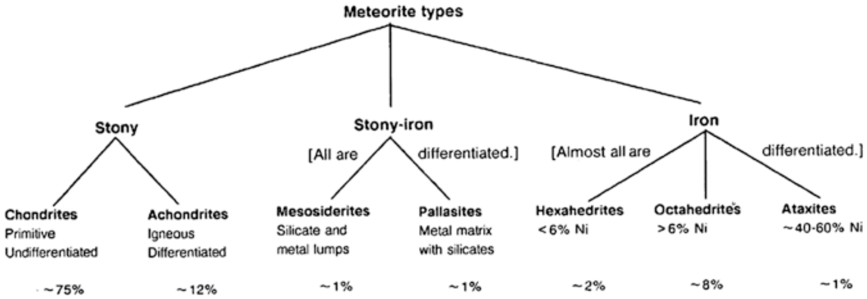

Figure 2.8 Meteorite taxonomy. Meteorites are classified into three large families, each with its subcategory. The percentage values show which meteorite samples are more often found and which are rarer.

Analysis of tens of thousands of meteorites by meteoriticists (professional students of meteorites) has identified three large families based on their principal composition, namely stony (also referred to as stones), stony-iron, and iron.

As Figure 2.8 indicates, the majority of meteorites are members of the stony family. Generally speaking, they primarily display an intricate mixture of silicates, metals, and sulfides. Depending on the traits of this mixture, stones are divided into chondrites and achondrites.

Chondritic meteorites are also labeled as primitive meteorites because microscopic examination of their inner structure does not display the telltale signs of sedimentation. Their parent material was never subjected to melting and heating sufficient to trigger gravity-based separation processes. Rather, the parent material was formed by simple accretion of material by gravitational attraction. This implies that the composition of such meteorites (and hence of the parent they came from) is undifferentiated, meaning the same throughout their volume regardless of the point being sampled. Furthermore, they are believed to be samples of one of the oldest materials in the Solar System, and due to the absence of sedimentation their composition closely reflects that of the region of the Solar System in which meteorite formed, at the time of formation. The majority of primitive stony meteorites carry within their bulk, glassy spheroids that range up to one centimeter in diameter called chondrules (from the Greek word ‘chondros’, which means grain or seed).

As shown in Figure 2.9, the chondrites are divided into carbonaceous (C), ordinary (OC), and enstatite (E). Carbonaceous chondrites are the richest in volatiles, and thus are the only type of meteorite to closely match the elemental composition of the Sun. This is because the Sun and the parent material of these meteorites originated from a single cloud of gas and dust in interstellar space. Common features that are shared by all carbonaceous chondrites include a high content of

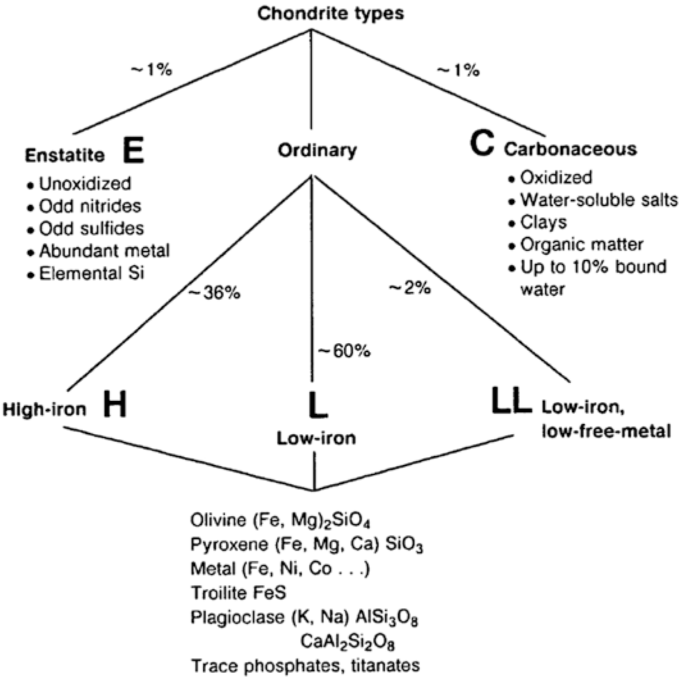

Figure 2.9 A breakdown of chondritic meteorite classes. It is easy to see how the chondrite meteorites display a wide range of compositional diversity.

carbon and organic material, plus the fact that the mineral phase is highly oxidized.

The taxonomy of carbonaceous chondrites (C) is based on eight groups, each of which is named after the closest place to where the first representative sample of that group was identified. Ordered in terms of most primitive (that is to say, most volatile-rich and thus most similar to the composition of the Sun) we have the CI (after Ivuna, Tanzania), CM (after Mighei, Ukraine), CV (after Vigano, Italy), CO (after Ornans, France), CK (after Karoonda, Australia), CB (after Bencubbin, Australia), CR (after Renazzo, Italy), and CH (where H refers to an exceptionally high content of iron and metallic iron). Generally speaking, C meteorites span a large range of mineralogies, parent bodies, and properties. A number of C meteorites are not associated with any of these groups owing to their having a peculiar composition.

The most abundant chondrites are the ordinary ones (OC). They show a uniform mineralogy, predominantly of olivine, pyroxene, troilite (FeS), plagioclase feldspar, and metal in the form of iron-nickel alloy. Because the OC acronym does not have any taxonomic significance it is only a convenient tag. In fact, the parameter which distinguishes different groups within this class is the total iron abundance, expressed as the iron-silicon (Fe:Si) ratio. Based on this, the high-iron and the low-iron groups were initially identified. Subsequently, a third group displaying an even lower Fe:Si ratio was identified and labeled LL.

The enstatite subgroup of the chondrites is characterized by an extreme state of chemical reduction, as evidenced by the presence of far less than 1% of iron oxide. As in the case of the ordinary ones, they are divided into two groups based on their total iron content.

The concentration of chondrules varies among the different groups of chondrites, and some stony meteorites are entirely devoid of them. This class is referred to as achondrites, and the lack of chondrules indicates their origin from a material which underwent differentiation where the metals and sulfides separated from the silicates. In other words, they originated from a parent body that did undergo differentiation by fractional distillation of molten magma, which upon cooling produced a crust and a mantle. For this reason, achondrites display a broad range of oxidation states which identify several subgroups.

While the stony meteorites are characterized by a composition which indicates an undifferentiated parent body (with the notable exception of the achondrites), both the iron and the stony-iron meteorites are from differentiated bodies. The irons are overwhelmingly composed of an iron-nickel alloy in which there are inclusions of a variety of other metals. Stony-iron meteorites are composed in approximately equal proportions of metal and stone, so they look like a mix of iron and stony meteorites. There are two subgroups, distinguished by their internal structure. The pallasites are identified by a continuous metallic matrix with lumps of silicates. The mesosiderites have chunks of metal dispersed discontinuously among chunks of silicates.

It is important to recall that this classification is based upon the space rocks that survived passage through the atmosphere. Other meteorite types likely exist that do not survive. For instance, carbonaceous chondrites have a weaker consistency which makes it difficult to survive entry intact. Extraordinary conditions are required for a carbonaceous chondrite to survive passage through the atmosphere, because most of them end up in fireballs. Although 75% of meteorites in collections are chondrites, only 1% of the recovered chondrites are carbonaceous. They are extremely reduced, have much lower abundances of volatile elements (and no detectable water), are rich in metallic iron-nickel alloy, and contain exotic minerals that are unknown on Earth such as calcium sulfide and a nitride of silicon. Meteorites with high quantities of a metal such as iron can readily survive entry and landing. What is more, they can stay on the surface for so long that weathering processes will destroy a stony meteorite, or at least it render it unrecognizable. Hence the strong bias towards iron meteorites as compared to stones.

THE METEORITE-ASTEROID RELATIONSHIP

In the early 1970s, MIT assistant professor Thomas B. McCord determined that the spectrum of Vesta, the second largest asteroid in the main belt, was an almost perfect match for the composition of the basaltic achondrite meteorite type. This discovery led to the realization that meteoritic material can provide significant insights into the composition of asteroids. In other words, if the spectral analysis of a given asteroid resembles that of an existing type of meteorite, then the composition of the asteroid should be fairly analogous to that of the meteorites. That is why meteorites are often defined as “poor’s man space probes” – with tens of thousands of samples collected, analysed, and catalogued, we have gained a good understanding of the composition and geology of asteroids even though only a handful of them have been visited and studied by robotic probes. In the absence of exploring in-situ or returning samples to Earth, the only way to determine the composition of a given asteroid is by analyzing the sunlight reflected from its surface. This spectroscopic analysis spans visible light to the infrared, and can provide a lot of information. The principle is straightforward: different minerals absorb light at different wavelengths, producing reflectance spectra with characteristic wavelength-dependent absorption features. The reflectance spectra of asteroids can be investigated by comparing the features observed telescopically with an extensive database of laboratory reflectance spectra of minerals and meteorites. Of course, this is based on how much light is received, using the rather intuitive rule that the brighter the surface, the more light is received. Distance and size also play roles in determining how much light reaches the observer.

This has led to the definition of a number of taxonomic systems aimed at making sense of the large variety and number of compositional spectra which were identified by intensive efforts to compile a census of the asteroids. Two of the most commonly used classifications are the Tholen and the SMASS. The former was first formulated in the early 1980s by American astronomer David J. Tholen, and proposes fourteen asteroidal types. The latter, which was created in 2002, has 26 asteroidal types. Three broad categories are common to both taxonomies: the C-group for asteroidal spectra similar to that of carbonaceous chondrite meteorites; the S-group for asteroids whose composition is closely related to stony meteorites; and the X-group for asteroids with a predominantly metallic composition as well as asteroids which have compositions entirely different from those in the other two groups.

Before we proceed further, it is necessary to emphasize that asteroid composition is far more complex than the portrait derived from studies of meteorites and analysis of spectra. In fact, to reach Earth, a meteorite has to travel along an Earth-crossing orbit. In the vast majority of cases their parent bodies will be NEAs. Consequently, such findings are strongly biased towards this class of asteroids rather than belt ones. In turn, this means that such meteorites are mostly derived from those narrow regions of the asteroid belt belonging to the Kirkwood gaps in which resonances with Jupiter divert belt asteroids into the inner Solar System.

Furthermore, telescopic reflectance spectroscopy can provide compositional data only for the surface of an asteroid, which may well have been modified by irradiation and collisional processes. Studies of the lunar surface have shown that the composition of the regolith can be strongly altered by exposure to the impact, thermal, and radiation environment of space. What the surface of an asteroid reveals might not match with its bulk composition. In this regard, the study of meteorites can provide a *better* picture of an asteroid than surface spectroscopy. In fact, the vast majority of meteorites have been identified as deriving from the interiors of asteroids, and so have not been subject to the alteration that occurs at the surface. Thus, meteorites are an excellent analogue whose mineralogy can be exploited to interpret the composition of spectrally similar asteroids. Determining the composition of asteroids in this manner is an extrapolation of data available from meteorites and weighting it to account for the effects of the space environment.

Several asteroid types are worthy of further discussion. For example, the C-type displays a strong affinity with the carbonaceous chondrite meteorite type. If we were to bake C-type asteroidal material, then on average the composition of the extracted material would consist of 92% iron, 7% nickel, and nearly 1% cobalt. We would also get a considerable amount of platinum-group metals (PGM). These are clustered in the Periodic Table and are important in a large number of technological applications from electronics to nuclear reactors. But the bonanza does not stop here. There would also be a mixture of silicates of magnesium, calcium, aluminum, sodium, potassium, titanium, and other rarer element. Depending on the quantity of water locked within its constituents, such an asteroid would also provide us with salts rich in potassium, sodium, halogens, and sulfates. Up to 99% of the mass of an M-type asteroid would be rich in metals, mostly an iron-nickel alloy, but there would also be PGM, carbon, nitrogen, sulfur, phosphorus, germanium, gallium, arsenic, and antimony, as well as other elements used in the production of semiconductors. An E-type asteroid (in the X-group) is typically an assemblage of minerals of metals such as titanium nitride, manganese sulfide, magnesium sulfide, nickel silicide, silicon oxynitride, and even silicon.

This compositional variety is a consequence of the dynamic events that occurred during planetary formation. We have already seen how the planetesimals would have coalesced to form proto-planets. Bodies hundreds of kilometers in diameter and rich in radioactive isotopes started to melt as a result of the heat given off by the decaying isotopes. In combination with a meaningful gravitational field, the heavier elements such as iron and nickel would sink to the center to form a metallic core englobed by a silicate-based mantle. Solidification of the surface of the mantle, composed of the lightest silicate-based minerals, would have formed the crust. Over time, such proto-planets would have been subjected to collisions which, depending on the speed and dimension of the impactor, would have excavated material that produced the variety of asteroidal and meteorite types observed today. For instance, a high-energy impact could penetrate and remove material from the mantle to produce an S-type asteroid. Or it could lead to mixing of mantle silicate material, such as that of the achondrite meteorites. A hyper-velocity collision between two bodies with similar dimensions would have resulted in the catastrophic break-up of both bodies, exposing the cores and giving rise to M-type asteroids. Additional collisions throughout the life of an asteroid would produce the populations of meteorites that are either destroyed upon penetrating Earth's atmosphere or are collected on the surface.

It is essential to bear in mind that asteroid composition is much more complex than the canvas painted so far by meteoritic studies and spectral analysis. Only by a program of in-situ exploration of a large number of asteroids will we get a data set sufficient to accurately assess what is available out there.

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IMAGE LINKS

Figure 2.1: Heiken, G., Vaniman, D. and French, B. (1991). *Lunar Source Book. A User's Guide to the Moon*. Cambridge University Press, p.38.

Figure 2.2: https://www.lpi.usra.edu/resources/apollo/frame/?AS17-M-1653

Figure 2.3: https://www.lpi.usra.edu/resources/apollo/frame/?AS15-M-1423

Figure 2.4: https://www.flickr.com/photos/nasacommons/9460228740/in/album-72157634974000238/

Figure 2.5: Heiken, G., Vaniman, D. and French, B. (1991). *Lunar Source Book. A User's Guide to the Moon*. Cambridge University Press, p.383.

Figure 2.6: https://cneos.jpl.nasa.gov/about/neo_groups.html

Figure 2.7: https://ssd.jpl.nasa.gov/?histo_a_ast

Figure 2.8: NASA SP-509 Space resources. Volume 3: Materials. (1992). [pdf] NASA, p81. Available at: http://www.ntrs.gov [Accessed 24 Jul. 2019].

Figure 2.9: NASA SP-509 Space resources. Volume 3: Materials. (1992). [pdf] NASA, p83. Available at: http://www.ntrs.gov [Accessed 24 Jul. 2019].

3

Off-World Mining

MINING 101

Before we can process the resources of a celestial body, we need to extract them and set up suitable facilities for their manipulation into a form that can then be used in the manufacturing of goods. In other words, we need to set up an out-of-this-world mining capability.

Generally speaking, a mining project begins with the identification of a market for one or more specific resources that can provide a conspicuous economic return. In fact, as for any costly and risky undertaking, it is vital to present a well-defined rationale to attract investors and assure stakeholders of the economic soundness of a project which, by its very nature, will not start to deliver returns until many years have elapsed.

Once a market has been recognized, the exploratory phase can begin. This involves a comprehensive program of mineral prospecting to understand the spatial distribution of the resource(s) of interest, together with issues of logistics, environmental pollution, local community worries, and so on. Large-scale regional and detailed local surveys will provide full insight into the potential offered by a possible future mining endeavor. Geochemical and geophysical remote sensing, aerial and satellite photography, stream sediment studies, outcropping studies, and limited core drilling are typically employed during this phase. Historical research can also produce valuable data. Taken together, these activities provide a good understanding of the geology, petrology and mineralogy of the area, and requirements such as transportation needs, water reservoirs, local labor force, local power supplies, equipment availability, and so on.

Hopefully, at the end of this process, one or more areas will have been selected as worthy of a detailed site evaluation. Typically, this is done by core drilling

D. Sivolella, *Space Mining and Manufacturing*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-30881-0_3

performed using a spatial sampling interval designed to obtain sufficient data points to be fed into mathematical models written using state-of-the-art proprietary software. The goal is to chart a three-dimensional overview of surface and subsurface ore grade distributions, geological formations that affect mining, the amount of waste produced by the mining, and so on. Accuracy is of paramount importance because models are the main drivers in estimating the profitability of a mining endeavor, as well in tracing the layout of the site and determining the logistics requirements. Simulations spanning the whole life of the mine will be run with parameters such as mining methods and production schedules to determine the most cost-effective modes of operation. In addition to defining the ore body, the final plan defines the overall project and must be updated throughout the life of the mine. Finally, the detailed design can select the mining processes and define the apparatus that will be required for extraction.

Most mining methods can be grouped into those that occur at the surface and those that occur underground. Selection of the relevant approach is based on factors such as the depth of the mineral deposit, the cost of overburden removal and disposal, the value of the land versus other uses (e.g., farming), and so on.

From a technical point of view, surface mining is simpler and it can provide earlier productivity than mining underground. Surface mines typically assume the appearance of an open pit or strip and require the removal of an overburden of waste from above the ore-rich material. Overburden removal is usually conducted with heavy equipment such as earthmovers, dragline excavators, and bucketwheel excavators. Once the ore is exposed, other apparatus moves in to break it up and load it into rail cars, haul trucks, or conveyors for transport to the processing plant. Underground mining is conducted for the extraction of mineral deposits located at depths that would make surface mining impractical. In this instance, the overburden is left in place and the target deposits are reached via a series of shafts, declines and tunnels that are dug by drilling and blasting, and which also serve as routes for hauling the extracted material to the surface.

Compared to underground mining, surface mining offers significant advantages in the form of economies of scale from equipment efficiency and flexibility of operations that permit easy relocation of the mining equipment within the area of the pit. An open mine can be brought into service in as little as one-tenth of an equivalent underground venture. However, underground mining becomes inevitable when the economic and environmental strain of removing a tremendous amount of overburden can no longer be sustained, despite being more complex and replete with technical issues involving health and safety. For example, unless tunnel shoring is applied there is the increasing risk of overburden pressure and rock instability threatening collapse. Surface mining can also be affected by rock instability in the form of rock falls and slope failures. An underground mine is a confined, noisy, dirty workplace requiring proper ventilation to remove potentially explosive and poisonous gases and dust. An adequate flow of air will also help to regulate the temperature. Large heavy-moving machinery is always a significant hazard to workers, especially underground. When explosives are used in an underground mine, they must be formulated to preclude the development of dangerous gas and dust explosions.

Other mining methods rely on fluids to reach and pump the resource to the surface. This is routine in the oil and gas industry. A similar modus operandi called hydraulic mining uses water power to fracture the rock and transport the gravel to a processing plant.

Once material has been extracted from the mine it must be readied for the complex chemical processing that will unlock the coveted resource(s). This is a crucial moment, because the extraction process will likely have produced a loose aggregate composed of fragments ranging in size from 20-200 cm. Such a coarse aggregate is inappropriate for any meaningful and efficient chemical processing to extract the desired resource(s). In fact, the typical chemical processes adopted for the extraction of resources from a feedstock will operate most efficiently when dealing with tiny particles, because these offer a greater reactive surface for the chemical process to act upon. Hence a relatively low-energy five-step process called mineral beneficiation (or dressing) will reduce the aggregate to fragments suitable for chemical processes. The initial step of beneficiation is to crush the aggregate in order to achieve fragment sizes in the range 0.5-2 cm. The second step is to screen out those pieces in need of further crushing from those that are ready for the next stage, in which the material is ground down to particle sizes smaller than 10 microns. Crushing, screening and grinding are carried out concurrently and are performed in stages to maximize the capacity and efficiency of these operations. The fourth step, known as sizing, aims to ensure that the grinding process has achieved the right ore size for the fifth step. This consists of concentration, and because it is largely dependent on the resource(s) being sought it exploits a relevant physical property. Thus magnetic separation is used for magnetic minerals, electrostatic separation for minerals that have electrical properties, gravity separation for minerals with differing densities, and so on. The type of ore and the location of the mine will dictate whether the mineral dressing process will be primarily a dry or a wet operation, the number of intermediate steps that each of the five major operations will involve, and the equipment required by each process step. By beneficiating the ore to an industrial grade feedstock, resource extraction can be more efficient and provide a greater harvest. Furthermore, it reduces the size, complexity, and energy demands of the equipment on the chemical processing plant.

It is here, at the processing plant, that the raw material can finally become the much-coveted purified resource for exploitation to produce the materials and products which make our society function.

The process of reducing a mineral into a pure form from its oxides is called mineral refining. It embodies thousands of years of our innovation and technological advances. Mineral refining is highly dependent on the resource that is being sought, as well as on the type of raw material. Generally speaking, it relies on an ample supply of water, air, oxidizers, reducing agents, chemicals, heat, and electrical power. For example, in iron smelting, where the iron ore is put into a blast furnace along with coke and limestone, these three components are arranged into alternating layers at the top of the furnace. As hot air is forced in at the bottom and up into the layers, the iron ore melts. The coke causes the limestone to react with the molten iron ore to produce a flow of pure molten iron and impurities (slag) that collects at the base of the furnace. Because the slag is of lower density, it can be skimmed off, leaving the pure iron to be poured into molds and ingots. In contrast, the production of pure aluminum requires large quantities of electric power and reagents. In fact, the aluminum ore is bathed in a sodium hydroxide solution which dissolves the aluminum oxide but not the impurities. Cooling the solution allows the aluminum hydroxide to precipitate and separate from the impurities. By applying heat, the aluminum hydroxide turns back into its oxide, which is dispatched to a molten cryolite bath where it is electrolyzed so that pure aluminum can collect at the cathode as oxygen is released at the anode.

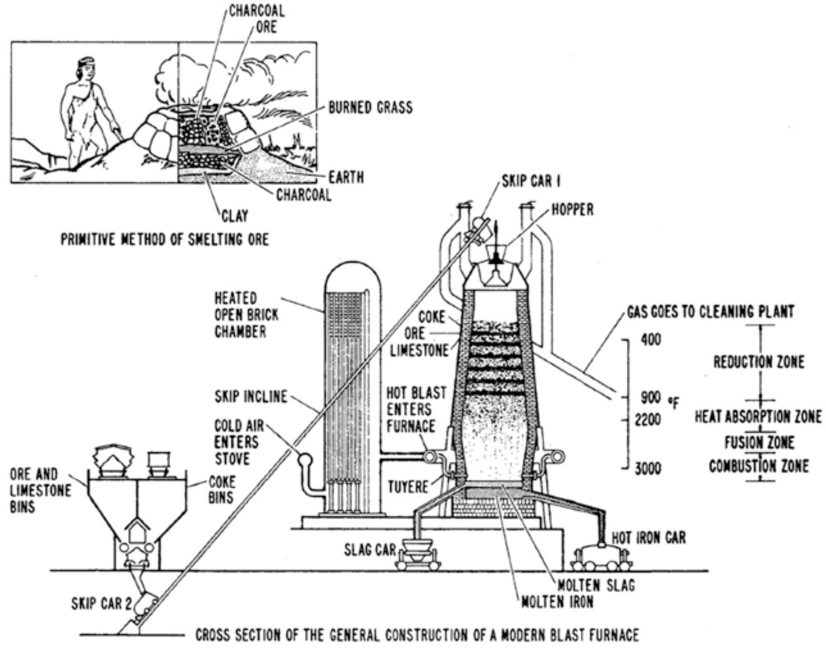

Figure 3.1 A cross-section of a modern blast furnace. Note how the primitive method for iron smelting is not that much different in principle from the current process.

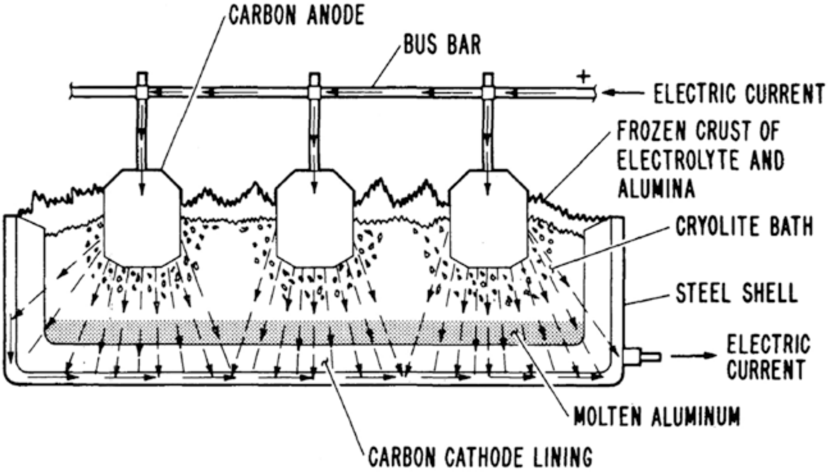

Figure 3.2 A schematic of an electrolytic cell for refining aluminum.

TERRESTRIAL VERSUS SPACE MINING

Resource mining is a practice as old as humankind, and in conceptual terms it has not changed much through history. Instead, increasingly more sophisticated apparatus and techniques for resource appraisal have facilitated higher efficiency, greater extraction capability, and increased economic returns. Mining on the Moon is still in the realm of sci-fi, in the pages of countless technical papers published by research institutions, and in popular science articles that promote expectations that will be difficult to satisfy any time soon and hence verge of speculative hard science fiction.

Given that the Moon is a rocky body, it is easy to imagine that well-understood and mastered techniques and processes widely employed in terrestrial mining will transfer at full value to our celestial neighbor, but this is not the case because the peculiar lunar environment will exert different effects on the machinery and processes. For instance, consider blasting on the surface of the Moon, where there is no atmosphere and gravity is one-sixth that of Earth. On Earth, the fragments will be rapidly slowed down by the air, and obliged by gravity to fall reasonably close to the site of the explosion. On the Moon, they will simply continue on their trajectory, eventually collecting over a broad sector far from the point of origin. In addition to requiring the clearance of a large area to preclude damaging equipment and harming astronauts, this will make retrieving the rock fragments an inefficient and time-consuming affair. Hence, if blasting is required on the Moon we will need to design and place explosives in such a manner as to reduce the scattering of fragments in that airless, low-gravity environment.

Gravity is also assertive in mechanical excavation, and the loading and hauling of loose material. The high gravity of Earth applies the weight needed to achieve traction, the horizontal force that prevents mobile equipment such as bulldozer-mounted rippers and scrapers from slipping during rock cutting and loading. The much reduced gravity of the Moon will require mining equipment to carry a lot of ballast, such as excavated overburden. Simply put, an excavator on the Moon will require six times as much mass as its terrestrial counterpart to create the same traction. This results in an escalation in inertia and a reduction in maneuverability. A possible alternative would be to develop tire treads or tracks that are optimized for lunar operations. Low gravity will also affect the hold-down of drilling equipment, requiring passive (weighting) or active (jacking) anchoring systems to ensure adequate drilling progress. On the other hand, low gravity will mean that tunnels and open mine pits are much less prone to rock instability and structural collapse, reducing the requirement for shoring of roofs and walls.

Although not strictly related to mining, the mechanical reduction or crushing of rock is an essential step in the process of working raw material to collect resources in a state useful for manufacturing. Although wet grinding to reduce the size of particles using high-pressure water is superior to dry grinding, there are difficulties concerning water production, delivery, containment and recovery that make it impractical at this time on the Moon. Dry grinding most often occurs in tumbling mills, where the size of particles is reduced primarily by impact action. Within a mill, a particle is lifted by the mill shell and follows a circular trajectory until forced by gravity to abandon that path and continue on a parabolic arc which causes it to crash against the bottom of the shell. Repeated impacts provide for particle fragmentation. If this methodology is utilized on the Moon, the geometry and working parameters (output rates, angular speeds, etc.) of the crushers will have to take account of the reduced gravity. This also applies to the activity which classifies particles by size. This occurs throughout the milling process. Usually, it is conducted in water, by exploiting how particles of different size distribute themselves through a column of liquid. For the same reason that wet grinding would be impractical on the Moon at this early stage, an alternative process would have to be developed for classifying particles.

Hard vacuum, wide temperature oscillations, dust accumulation, and radiations are other aspects of the lunar environment that will influence the design and use of mining equipment. For instance, seals and bearings will have to be guarded against the outside environment to prevent the boiling off of lubricants and mechanical erosion from the ingestion of abrasive dust.

The lunar environment is dominated by two weeks of continuous sunlight followed by an equal period of darkness. This raises questions about the brittleness

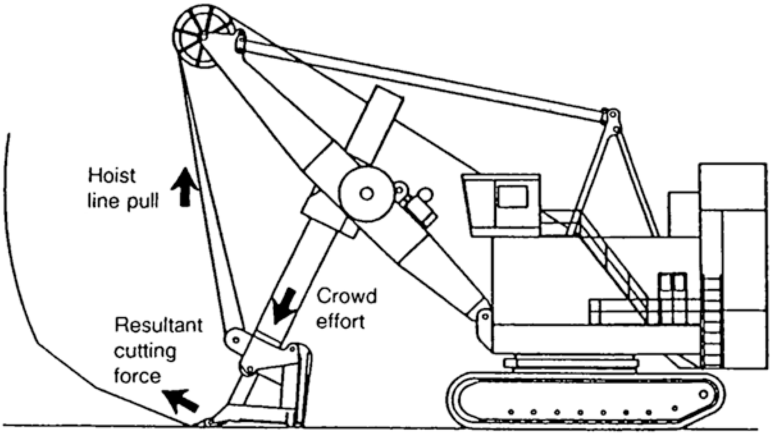

Figure 3.3 A simplified force diagram for a conventional mine shovel. The cutting force is a function of the hoist line pull, crowd effort, and front-end geometry. Large machine weight is needed to provide horizontal resistance to slippage during digging.

Figure 3.4 A good muck pile is well-fragmented and largely contained in one heap. Loading would be much more time consuming if the rock were widely dispersed, as might be the case using conventional blasting in a low-gravity environment and the absence of air resistance. The loading machine must have sufficient traction (created by friction and weight) to push the loading bucket into the muck pile.

of materials and the thermal control of equipment. Thermal control requires an appropriate level of cooling and warmth during the lunar day and night sessions, respectively. A variety of passive and active cooling systems have been developed through the decades of space exploration. Incorporating these into lunar mining

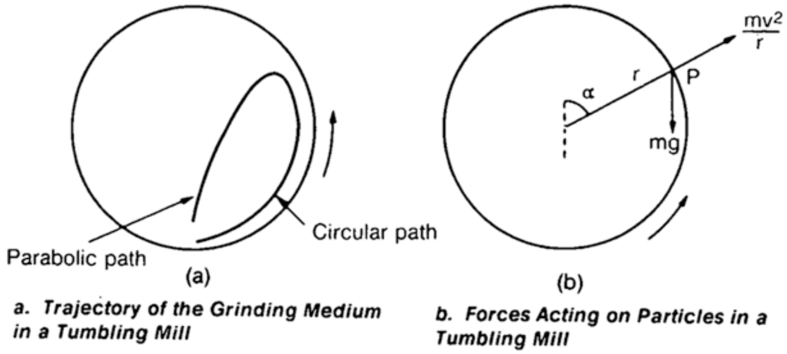

Figure 3.5 A conceptual representation of the physics of a tumbling mill. At point P the weight of the particle is balanced by the centrifugal force. At this moment, the particle abandons the circular path imposed by the tumbling drum and follows a parabolic arc to the bottom of the drum, with the impact provoking breakage. It is evident how gravity affects grinding.

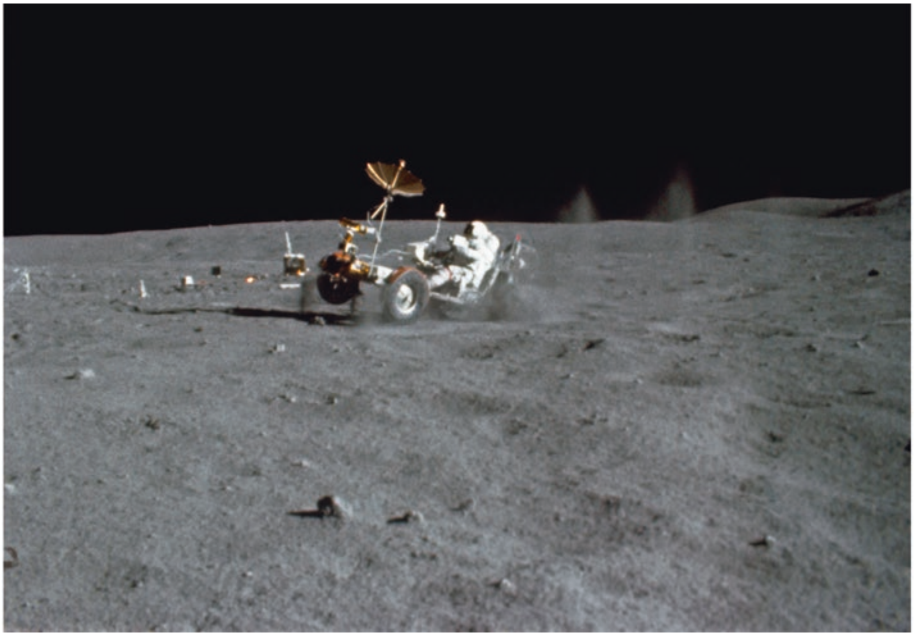

Figure 3.6 A still frame from a motion picture showing Apollo 16 Commander John W. Young driving the Lunar Roving Vehicle on the Moon. Although a small vehicle, it stirred up a great deal of dust!

equipment will greatly increase their mechanical sophistication. Heavy shielding can limit heat leaking in from the outside in full sunlight. Large radiators can dissipate internal heat to space. There will have to be precautions to preclude coolant fluids evaporating in the hard vacuum. The absence of an atmosphere will complicate the management and retention of fluids in drilling operations. On Earth, in addition to cooling drilling bits, fluids carry the cuttings away from the hole. Such fluids would be rapidly lost on the surface of the Moon. It will be necessary to create a different rock drilling technology (e.g., rock melting, which will be discussed below). The electronics driving the mining apparatus will be sensitive to electromagnetic radiation, cosmic rays, and charged particles in the solar wind. This is a well-understood issue that affects all hardware dispatched into space, and solutions are readily available. Hence their incorporation into lunar mining equipment ought not to add much complexity.

MINING ON THE MOON

Design of Lunar Mining Equipment

Science fiction has accustomed us to the idea of gargantuan machines trundling on the surface of the Moon or other celestial bodies, grinding everything in their path to feed an equally vast industrial mining and processing activity. One day we will gain such a capability, but it would be irrational to presume it from day one. It would be as if, after the first test of their Flyer in 1903, Orville and Wilbur Wright had immediately set out to build the supersonic airliner Concorde!

Although terrestrial mining is a mature undertaking, we do not have any experience in off-world mining. Considering how the lunar environment will affect the design and use of mining equipment, we need to start simple and progressively advance to higher levels of sophistication.

Generally speaking, lunar mining equipment should be distinguished by simplicity, ruggedness, robustness, versatility, low energy consumption, inclusion of automation, and low cost. Simplicity entails a design that produces equipment resistant to failures for ease of repair and reduced downtime for maintenance. The fewer moving parts, the better. It also includes the ruggedness and robustness traits. The very nature of mining imposes a heavy penalty of wear and tear on excavation and hauling apparatus because the continuous impact and abrasion requires frequent resurfacing and replacement. The temperature swings will also impair durability. Mining machinery will therefore have to make use of tough materials designed to minimize wear and extend the time between replacement of parts and overhaul. Given that it would be inconceivable to expect that every attribute of an extraterrestrial mining undertaking will be accounted for prior to commencing the first excavation, the equipment must incorporate sufficient versatility for rapid relocation, reorientation, alteration in distribution network, and other changes that become necessary during the operational phase. The same equipment should also be designed to accept alterations and upgrades to its hardware, and possibly be able to operate in a number of different modes.

Lunar Mining on the Surface

Given our lack of experience in extraterrestrial mining, common sense dictates that the initial lunar mining activities are conducted on the surface. Furthermore, they will not require the excavation and processing of the tremendous tonnage of rocks typical of terrestrial mining. The first lunar mining site will not be initiated for industrial-scale production, but as a proving ground to learn by trial and error what is required to mine a celestial body. The results will be fed into the design and planning of future sites and equipment for large-scale mining.

The prospective excavation apparatus for the first small-scale mining operation on the Moon could be the so-called three-drum slusher, also known as the cable-operated drag scraper. It is a century old, and not as efficient as modern methods, but it complies with the requirements discussed above and has a proven track record. In other words, it could be rapidly applied to the lunar environment and deliver experience in operating on the lunar surface.

The slusher apparatus consists of three drums around which a cable is wound, three lengths of cable to operate mining tools such as a scraper, and two anchored pulleys. There is also a mobile power/loading unit. Setting up the apparatus starts by emplacing the two anchors and mobile power/loading unit at locations which outline a triangular-shaped mining site. Depending on the consistency of the surface, a suitable anchoring system will be used to secure the pulleys and mobile unit to the firm regolith that lies beneath the loose superficial material. By setting the tensions on the cables that stretch between the pulleys and the mobile unit at the apex of the triangle, the scraper can be positioned at any point within the site. Once the scraper is in position, it is hauled back to the mobile unit. There the collected material is discharged into a suitable apparatus (such as a conveyor belt) for transport to a processing site. For the sake of simplicity, it would be advantageous to have a mobile processing unit stationed near the mobile power/loading unit.

The slusher system offers the benefit of defining its own mining site. Although the usual layout is a triangle, by changing the number of pulleys and their positions other shapes can be mined, such as rectangles and right angles. Among the other advantages is the fact that only a small inventory of spare parts need to be shipped from Earth and the downtime can be kept to a minimum in the event of breakage or maintenance. The simplicity of the hardware is reflected in the limited number of bearings and moving parts. This will minimize the risk of mechanical seizure due to penetration by dust and evaporation of lubricant. The inherent simplicity of the apparatus will also minimize the cost of adapting it to the environment. A scraper also offers great flexibility. It can be reconfigured, or relocated, in the event of encountering an insurmountable obstacle in the pit. The possibility of using different excavating tools attached to the cable will allow for rapid adaptation to the surface condition of the pit. For instance, a dozer blade can be used to remove undesirable rocks from the pit. If finely grained materials are required, the system can be fitted with a rake to transfer oversized rocks to the far side of the pit, then be fitted with a scraper to collect the fine material.[1] Rippers and plows can be employed to break hard ground and to increase the working depth. By varying the bucket size, span, reach, and motor power, the amount of material excavated with each scrape can be varied. In the low lunar gravity it may be convenient to artificially weight the scraper, or reconfigure the cable force system, or both, in order to optimize the vertical penetrating force of the bucket to collect the best load. Low gravity might enable not only an easier loading of material into the bucket but also its escape in the case of a bumpy ride. In fact, in this latter case, because of the low gravity, the bucket would be more sensitive to a ride that sloshes the material in the bucket, causing it to spill into the pit. Reconfiguration of the cable system and altering the various tensions should minimize such losses.

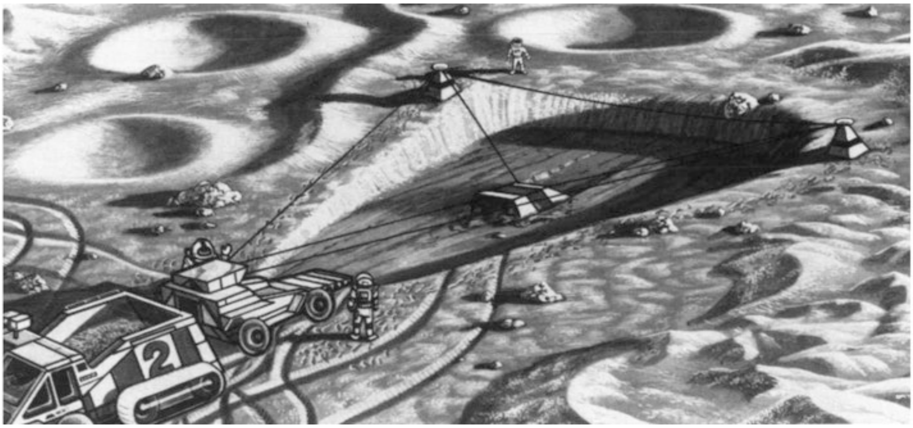

Figure 3.7 A perspective view showing several features of a mobile slusher. The scraper in the center of the pit continues to fill with material until it reaches the discharge point or loading station on the left. Note how the box type slusher bucket has enclosed sides to prevent the very finely grained lunar material from spilling out during loading and transportation.

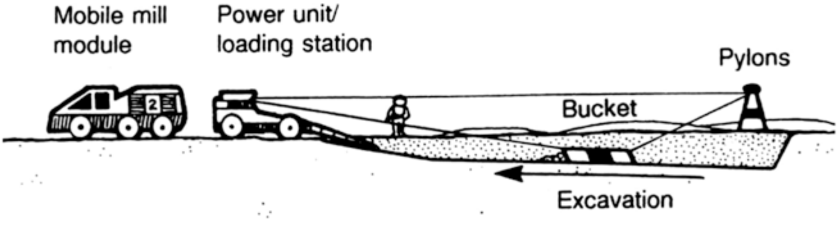

Figure 3.8 A side view of the model lunar slusher, showing how the material from the bucket is dumped directly into the mill module. Note how the pulleys installed on top of the pylons position the bucket during its return to the mining area from the loading station.

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[1] Finely grained regolith is sometimes referred to as 'fines'.

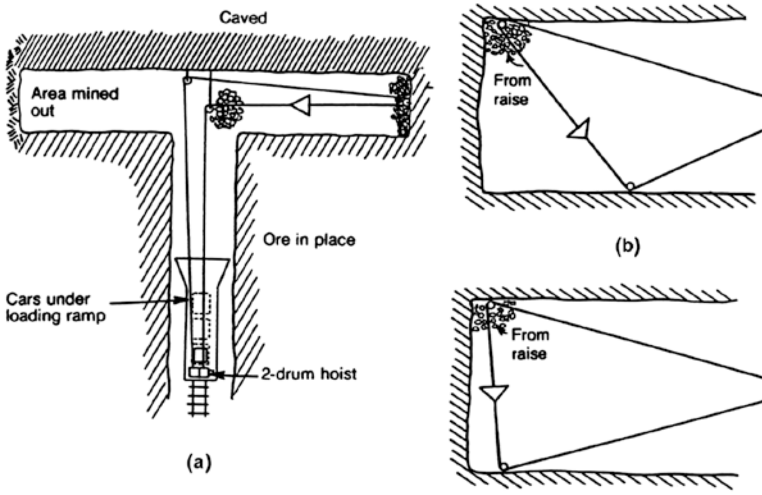


Figure 3.9 Slusher mining patterns: a three-drum slusher scraping around a corner (a); and a changing setup that enables a two-drum slusher to mine outside its restricted narrow path (b). In (a) the load is discharged onto a ramp to the cars of a train that will take it directly to a processing plant.

A more sophisticated approach would involve loosening the regolith first, followed by collection and delivery to a processing plant. The loosening could be achieved by bladed rollers, explosives, augers, and scarifiers. Blade rollers consist of a drum fitted with radial blades. Straight blades require less power. Curved blades disrupt more the surface. In the low lunar gravity the drum must have sufficient weight to keep its blades pressed against the surface. Rocks could provide the ballast. The disadvantage of this kind of apparatus is that it relies upon forcing the blades to cut deep into the soil, which increases the force that resists forward motion and necessitates using a more powerful vehicle.

If explosives are employed out in the open, they will have to be placed beneath the surface and in a grid pattern that opens a shallow crater. If the situation requires it, they could be positioned at the base of a large crater in order to shear its rim in such a way that the debris collects inside the crater. As noted earlier, blasting in low gravity will require the formulation of explosives and the calculation of grid patterns that will not cause regolith to fly far from the work site.

Augers are also effective in loosening regolith. They are similar in principle to the bladed roller, but in an auger the blades are oriented so that the regolith is churned into a central aisle. The advantage of the auger is it sheds the regolith as it rotates. Scarifiers are rakes where a platform is dragged along the surface with the blades pushed into the ground. In low gravity, it will be necessary to use ballast.

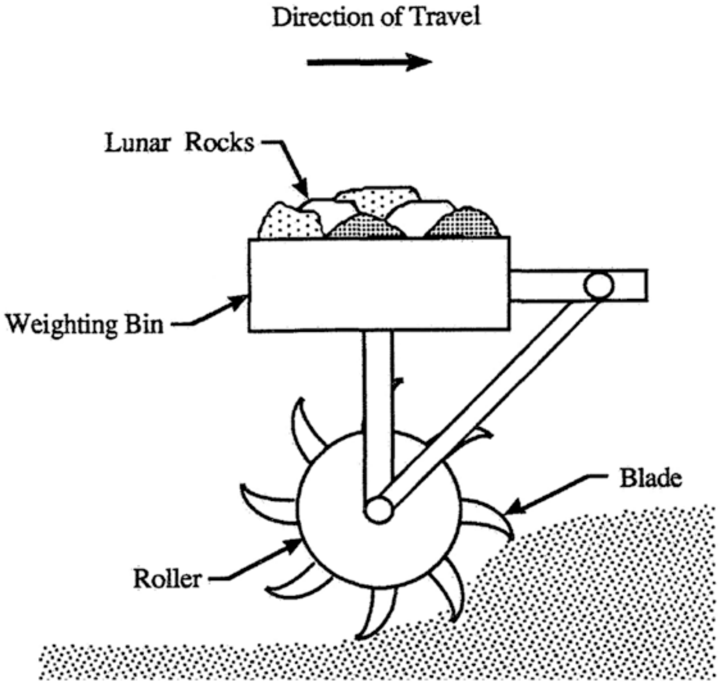


Figure 3.10 A schematic of a bladed roller for loosening regolith.

Collection of the loose regolith can take place by means of conveyor belts, inclined planes, bucketwheels, and front-end loaders. The conveyor belt is attached to the front of the collecting bin, minimizing in this way the length of the conveyor while reducing the number of moving parts and hence the overall mass of the system. In a variation of this device, an inclined plane is positioned forward of the conveyor belt. The forward motion of the collector pushes the regolith up the inclined plane and onto the conveyor belt. This minimizes wear on the belt because it is the inclined plane which pushes on the regolith rather than the conveyor belt. Also, there is no torque on the end of the belt because the cutting force acts on the inclined plane. Another combination would be to position the loosening device (e.g., a scarifier or auger) in front of an inclined plane to accomplish the loosening and collection at the same time, using a single vehicle. The advantage of an inclined plane is its simplicity and reliability. The disadvantage is that it requires power to operate effectively, because much of the regolith will end up being pushed in front of the plane rather than forced up the incline. This resistance to forward motion must be counteracted. A bucketwheel collection vehicle has the advantage that it is widely used on Earth and its design and behavior are well known. But it does have a large mass and volume, and the number of moving parts reduces reliability. The large mass is, however, an advantage because it allows a bucket to cut deep into the regolith, which eliminates the loosening stage.

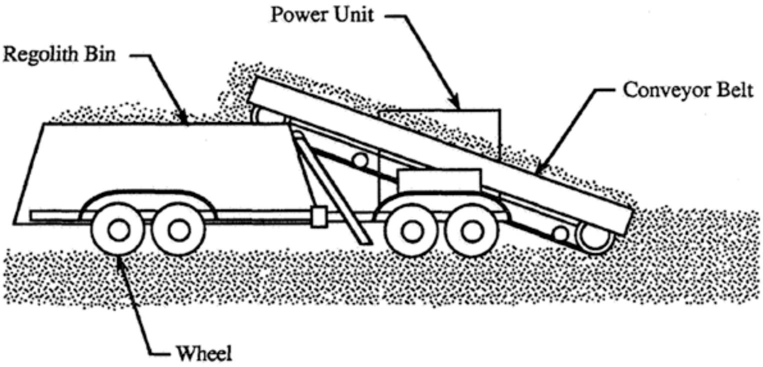


Figure 3.11 A schematic of a conveyor belt collection system.

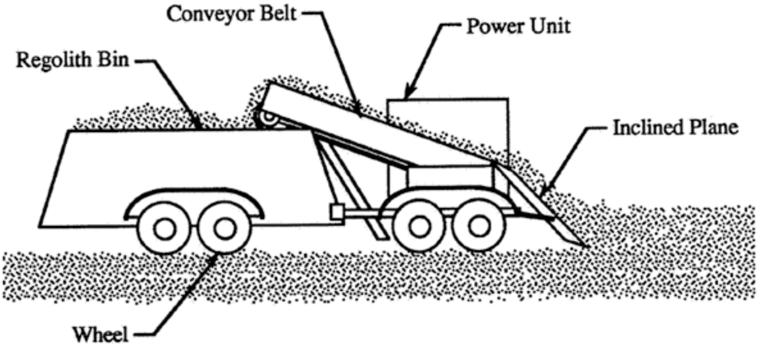


Figure 3.12 A schematic of a conveyor belt with an inclined plane collection system.

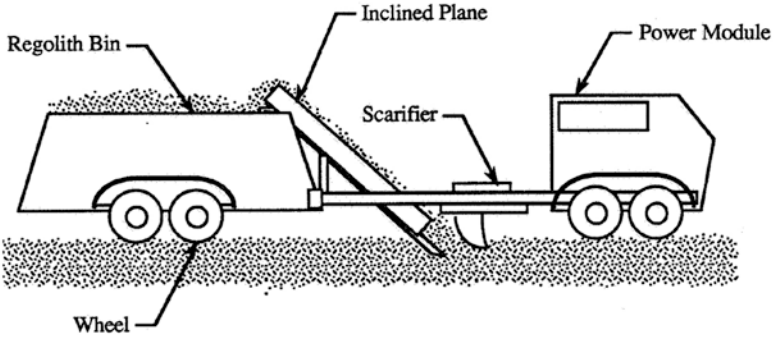


Figure 3.13 A schematic of an inclined plane and scarifier collection system.

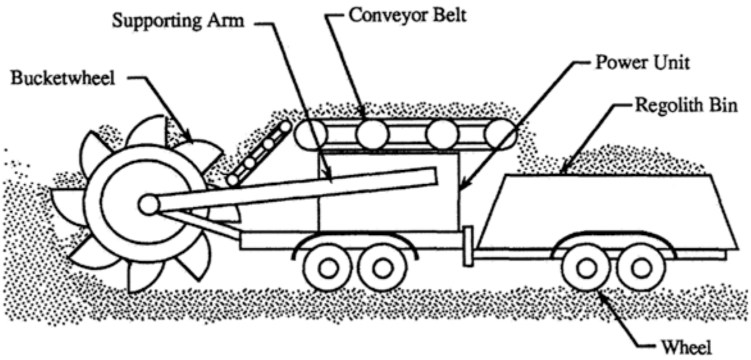


Figure 3.14 A schematic of a bucketwheel collection system.

Underground Lunar Mining

Just as on Earth, underground mining on the Moon will have to be considered when access to a resource from the surface becomes impractical. In fact, underground mining should take place as early as possible to obviate exposure of astronauts and equipment to the inherent dangers of the surface, most notably temperature extremes, meteoritic bombardment, and radiation. Furthermore, working underground offers benefits such as simultaneous access to ore and living spaces. That is, as tunnels are dug out and ore is removed, the voids can be converted to living quarters, workshops, control centers, and any infrastructure of a self-contained outpost. Sealing off the entrances to tunnels will enable mining activities to take place in a benign environment, characterized by pressurized and shirt-sleeve working conditions. In this way, the reliability and lifetime of apparatus will be considerably extended because it will not need to be designed to withstand vacuum outgassing, thermal variations, radiation, and damage from dust.

On Earth, underground mining is frequently threatened by water, either because of pressure, excessive flow, or both. This will not be an issue on the Moon, which lacks flowing water. In general, the low gravity will minimize the risk of structural instability and collapse. Nevertheless, this could become an issue if it is necessary to gain access to weak or disintegrated ground. In this case, wall reinforcement will be no more of a challenge than it is on Earth. Another motive for underground mining may well be the desire to leave as much of the surface as possible intact, to preserve the external lunar environment for scientific studies as well as to conserve a natural wonder.

As in the case of surface mining, the early underground mines can be expected to adopt an approach based on modifying existing terrestrial equipment for lunar use. For instance, a caterpillar-crawler electric-powered vehicle capable of combining drilling, blasting, and ore removal actions would drive a number of drills into the rock face of the tunnel. After explosives have been inserted into these tubes, the rig would withdraw and the charges detonated remotely. Once the dust had settled, the rig would return and commence ore loading operations using a bucket to collect the broken rock and deliver it to a hopper that discharged onto a conveyor. This would offload the material onto a continuous conveyor train for transport to the processing plant. If necessary, the mining rig could be fitted with an automatic roof-bolter to reinforce the ceiling of the tunnel.

Using explosives in the confined space of an underground mine will always pose a risk to workers and apparatus, regardless of the celestial body on which it occurs. Even more so when the tunnels are later to serve as a base. In fact, proximity to the amenities necessary for the habitation and working requirements of the lunar mining community might rule out the use of powerful chemicals. Alternative and more advanced methods of rock fracturing should be evaluated. For instance, rock fracturing could be achieved by means of a high-temperature heat flux applied to a discrete area of the rock face. A hot spot within the target rock will force thermal expansion into the surrounding colder material which, being restrained from free expansion, will eventually yield to the rising inside-out mechanical expansion and shatter. Such a heat flux can be achieved by way of gaseous combustion, electrodes, ionized plasma, electron gun, microwaves, optical solar, and laser. If exceedingly high temperatures can be achieved, such as the plasmas produced by a nuclear fusion reactor, the rock could even be melted rather than merely fractured. In that case, the molten ore could be channeled into an electrolytic separator where an electric field isolates the minerals from the melt. The minerals are solidified in molds for ease of storage and transportation to the processing plant. In the meantime, the unwanted melt is directed towards the surroundings of the machine, where it cools to line the wall of the tunnel. Systems like this are widely portrayed in science fiction, and have already been developed for small scale applications such as drilling holes for the emplacement of explosives. Adapting such devices for off-world mining should be simple, because they are largely self-contained. The small number of moving parts will minimize maintenance. And by operating in a tunnel they will not lose traction in low gravity. As observed earlier, these are highly attractive traits for machinery destined to work in the alien environment of the Moon.

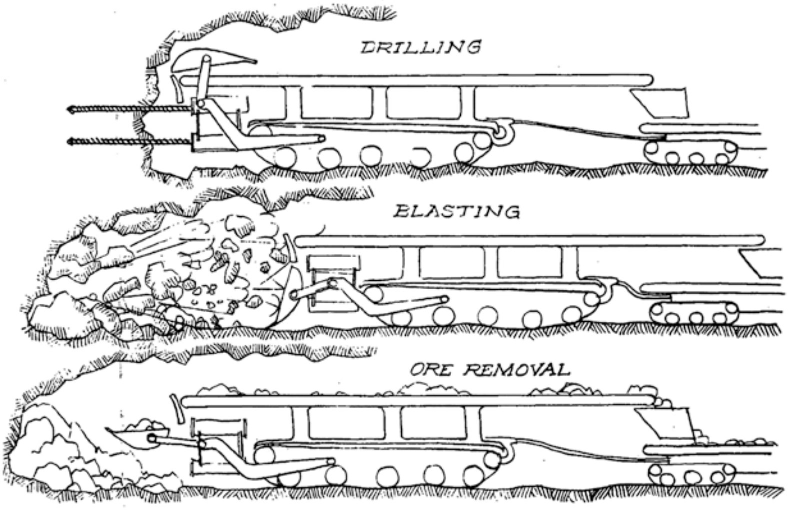
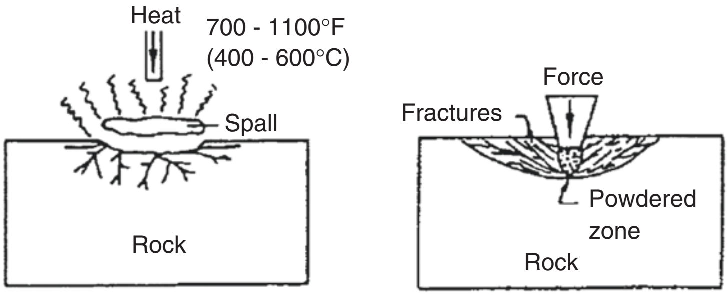


Figure 3.15 A conceptual automated lunar mining apparatus and operating sequence.

ASTEROID MINING

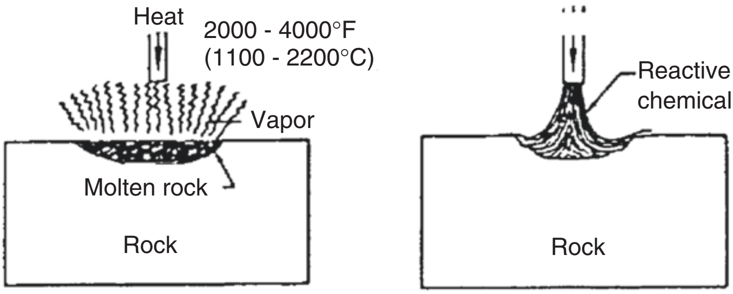
Asteroids will be attractive targets for off-world mining. Given their size – the largest, Ceres, having a diameter of less than a 1,000 kilometers – it is easy to appreciate how the exceptionally low gravity will have to be taken into consideration when designing apparatus to dig into what may prove to be hard rock. For instance, consider the manner in which the Philae lander was to settle onto comet 67P/Churyumov-Gerasimenko on November 12, 2014. As the European Space Agency explained in advance: “Philae will reach the surface at roughly walking pace, around 1 m/s. That may not sound like much, but as the comet’s surface gravity is roughly a hundred-thousand times weaker than Earth’s, a sophisticated system must be used to prevent it from rebounding into space. The three-legged landing gear will absorb the momentum and use it to drive an ice screw in each foot into the surface. At the same time, two harpoons will fire to lock the probe onto the surface and a small thruster on top may be used to counteract the recoil of the harpoon.” Despite the planning, Philae rebounded from first contact and when it was eventually pulled down by the weak gravity it settled on its side. This was a far cry from the soft, effortless touchdowns envisaged by science fiction. By the way, Philae was just 100 kg and it did not have to dig tons of rocks for resource extraction! Imagine what it would take to soft land an apparatus of several tons on the surface of a low-gravity body.

In the case of asteroids, mining activities will most likely initially take place on the surface. With such low gravity, one problem will be to prevent the fragmented



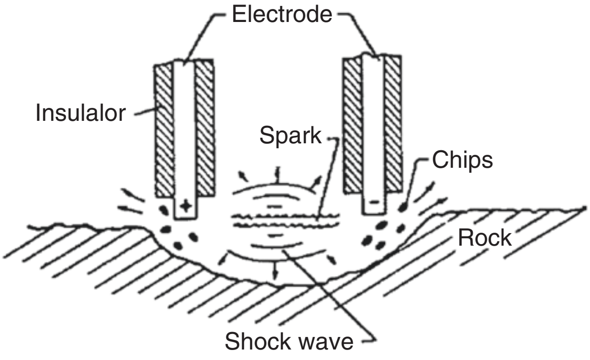
a. Spalling

c. Mechanical Stress



b. Melting and Vaporization

d. Chemical Reaction



e. Spark Cratering

Figure 3.16 Methods for rock disintegration. Spalling induces high thermal stresses by rapid application of intense heat (a). Melting liquefies rock by raising its temperature (b). Applying physical forces to the rock to exceed its mechanical strength (c). Using chemicals to dissolve rock bonds (d). Spark cratering is a variant of the mechanical stress method in which discharging sparks between electrodes generates pressure pulses that in turn chip the rock (e).

material from escaping to space. Even a gentle kick from a shovel will be enough to send rubble and lose particles into an orbit of their own around the Sun. More forceful methods of cutting material from the surface will only exacerbate this issue. This could represent a considerable loss of valuable resource. Dust and finely grained particles could linger in the vicinity, obscuring vision and clogging instruments necessary for teleoperation or monitoring of automated systems. Unless the mining apparatus is shielded, it could be damaged by floating debris. And a heavier, rugged design will be more expensive to develop, launch and deliver.

One possible solution is to exploit the issue rather than fight against it. For instance, in a study conducted by NASA in the 1990s on the exploitation of space resources, it was suggested that cables be placed around the asteroid, each carrying and acting as a travel guide for a cutter head or rock-fracturing device. Such a tool would fracture and excavate the soil by launching it from the surface. The expelled material would then accumulate in a flexible bag stationed above the area that is being mined, held in place by the same cables as are wrapped around the body of the asteroid. The rotation of the asteroid would assist in maintaining the shape of the bag. As one mining site becomes depleted the bag can be maneuvered to another one. Once the collection bag has been filled, it will detach and fly to a processing plant at some suitable place (perhaps in low Earth orbit). A new bag will be fitted to the asteroid for further mining operations. It is a rather simple method, perhaps less glamorous than that typically portrayed in science fiction, but equally effective. In fact, placing a cable around an asteroid might be easier than anchoring a spacecraft. For instance, if an auger is used for the anchoring, then a hold-down device has to be added to counteract the reaction of the soil to the auger's penetration. Hence an asteroid with a very low strength would be excellent for mining but difficult to anchor to. This is likely to be the case for most asteroids of interest. The cable solution is therefore attractive. Furthermore, producing a cable and stowing it in a compact container is relatively easy, and we have experience of this in terrestrial and space applications.[2] Also, because the cutter tool will run along its cable the issue of dust clogging vision and instruments is less relevant.

The same NASA report also proposed a variant in which explosives would blast a large block of an asteroid into the bag. This would be done in cases where the cutter would have difficulty negotiating the terrain. Cables would still be needed to guide and hold in position the drilling machines that would bore the blasting holes into the surface at locations calculated to produce the desired pattern of explosions.

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[2] A notable space application is the tethered satellite experiment carried by two Space Shuttle missions in the 1990s. Both were tasked with deploying a small satellite that was linked to the Orbiter by a 20-km-long tether to study the dynamical properties of a tethered system in the weightless environment of space and undertake research in the electrodynamics of the ionosphere. Although plagued by a number of significant complications, both flights accomplished their scientific and technological objectives.

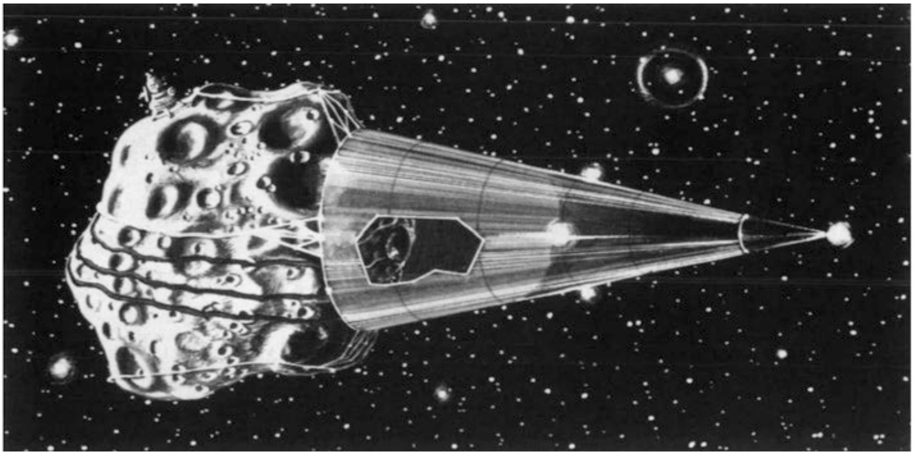

Figure 3.17 The cable-cutter-bag asteroid mining concept.

The cable-cutter-bag mining concept is well-suited to asteroids which are at least several hundred meters in diameter, because there must be sufficient room to move the cutter tool. It is likely to be impractical for a large block detached by explosives. Some other method would therefore be required to further process such blocks.

At this point we could employ a process called optical mining. It relies on focusing the raw power of the Sun to generate an intense beam of light with which to carve the surface of the asteroid. Simply put, it is a high tech version of using a magnifying glass on a sunny day to initiate a fire. Experiments have shown that by focusing sunlight on an area of just a few square centimeters, localized heating can raise the temperature to 1,300°C. This thermal energy needs only to penetrate a few millimeters into the surface for the shock to trigger fracturing. This is called spalling. If the rock material contains volatiles such as water and carbon dioxide then the heat will induce a rapid expansion, causing outgassing that will transport the fractured material away, thus exposing a new fresh cold surface on which to continue the process. This could rapidly penetrate deep into an asteroid, particularly if it is highly porous. However, not all asteroidal types are rich in volatiles.

One company that is working to produce and fly a spacecraft for optical mining is TransAstra, under a NASA contract for NIAC.[3] Founded by Dr. Joel C. Sercel, the company is advocating the so-called Asteroid Provided In-situ Supplies (APIS) architecture which consists of a low-cost low-mass spacecraft called HoneyBee. This vehicle features an inflatable system designed to capture,

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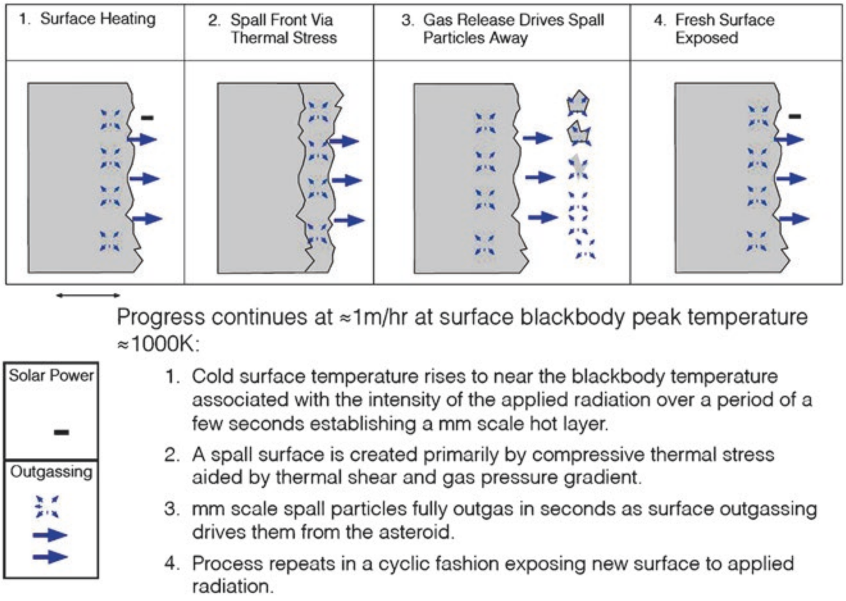
[3] The NASA Innovative Advanced Concepts (NIAC) program was established to nurture visionary ideas that might lead to breakthroughs in the exploration and settlement of space.



Progress continues at ≈1m/hr at surface blackbody peak temperature ≈1000K:

1. Cold surface temperature rises to near the blackbody temperature associated with the intensity of the applied radiation over a period of a few seconds establishing a mm scale hot layer.
2. A spall surface is created primarily by compressive thermal stress aided by thermal shear and gas pressure gradient.
3. mm scale spall particles fully outgas in seconds as surface outgassing drives them from the asteroid.
4. Process repeats in a cyclic fashion exposing new surface to applied radiation.

Figure 3.18 A schematic of the spalling process by optical mining.

de-spin, and hermetically enclose an asteroid of 10-15 meters diameter. Following capture, two large thin-film lenticular inflatable reflectors will be deployed which, using an appropriate mirror configuration, will concentrate sunlight inside the containment bag onto the surface of the asteroid for optical mining. We have already seen that optical mining exploits the outgassing of superheated volatiles to drive away the fractured surface rocks and expose fresh rock. This process will be extremely marked in the rarefied atmosphere of the containment bag (estimated at 10^{-4} atmospheres). Slowly but surely, this will crumble the asteroid to nothing.

As TransAstra seeks to mine asteroids for water,[4] the released volatiles will be cryopumped at moderate temperature into a passively cooled thin-film-enclosure storage tank, where the water will be stored as solid ice. A hard-shell storage tank is therefore unnecessary. Passive cooling is achieved by a surface mirror coating that emits infrared radiation and reflects sunlight into deep space. The system of mirrors will pivot to continually face the Sun as the asteroid travels along its orbit.

On completing its mining activities, the HoneyBee spacecraft would use its two solar reflectors to redirect sunlight into an upgraded solar thermal rocket known as

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[4] Water is fundamental for continuous expansion in space because it can serve as propellant as well as cater for basic human needs such as hygiene, food consumption and oxygen production.

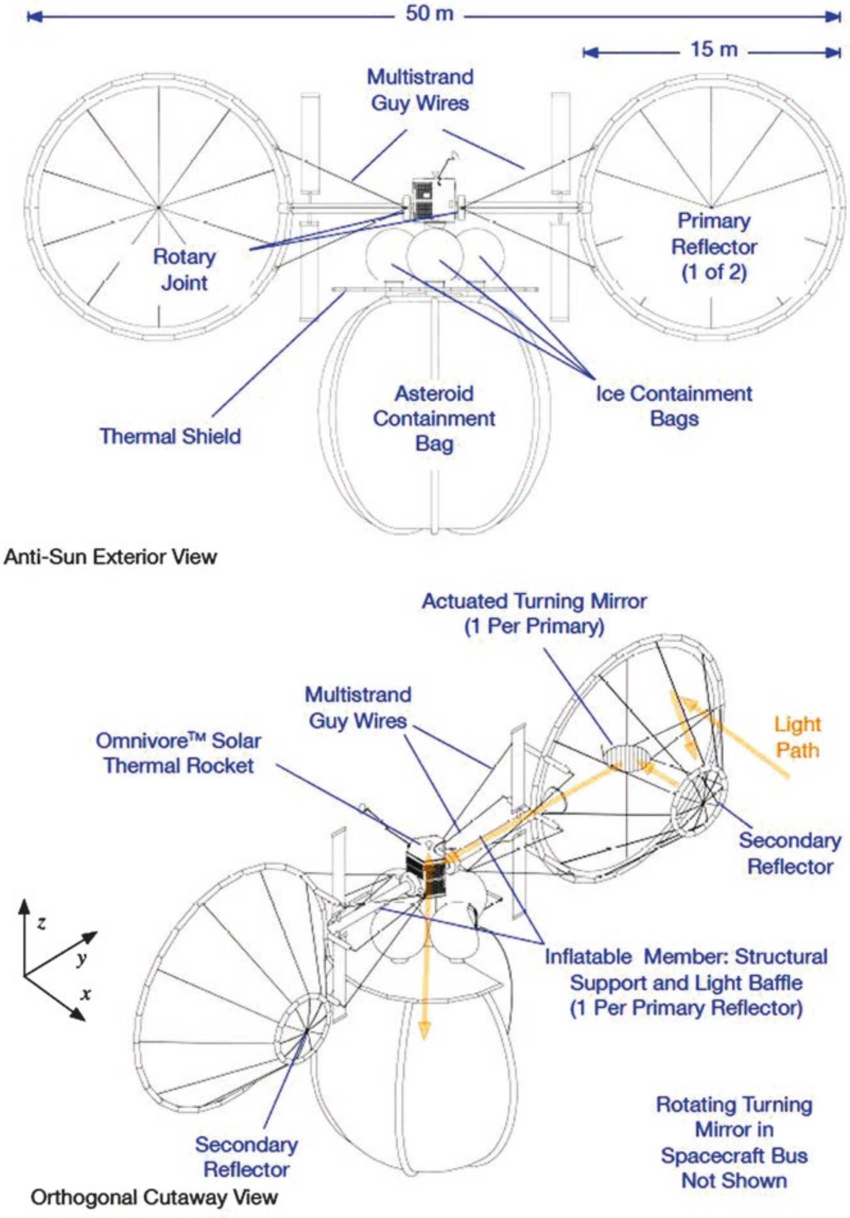

Figure 3.19 A schematic overview of the main elements of the HoneyBee Optical Mining spacecraft.

the Omnivore Thruster. Generally speaking, a solar thermal rocket uses sunlight to directly heat a reaction mass that is then passed through a nozzle to generate thrust. The hardware of a typical solar thermal rocket demands high purity

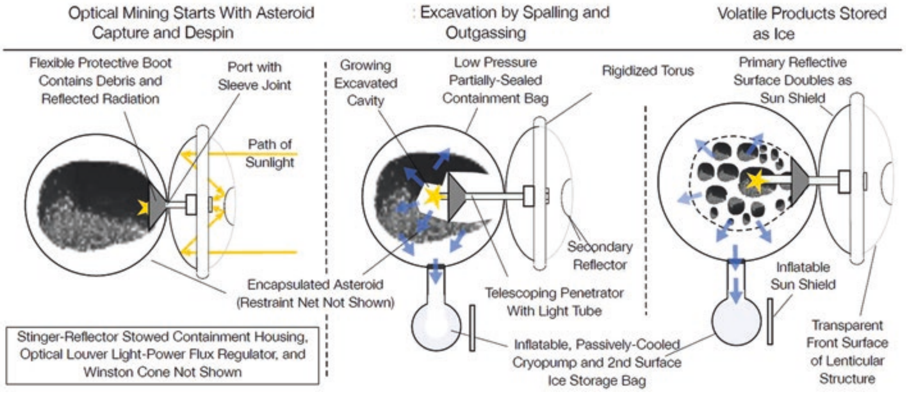

Figure 3.20 The optical mining process.

propellant, but the Omnivore Thruster is designed to accept the unpurified water extracted from the asteroid. At the heart of this thruster is a 3D-printed ceramic foam that, by absorbing the sunlight directed from the reflector, achieves high internal temperatures without melting or degrading its mechanical properties. Some of the collected water is then melted and pumped to the thruster, where it collects the heat absorbed by the foam and warms to a temperature sufficient to accelerate the propellant into the nozzle. In this way, the design saves the mass and cost of a dedicated apparatus for purification, instead requiring only coarse filtering to avoid clogging the ceramic foam.

The HoneyBee spacecraft might not look as cool as the gargantuan machinery in science fiction, but it is a promising start and offers several advantages. For instance, the overall mass and volume at launch are significantly reduced because it employs inflatable components for the reflectors, storage tanks, and asteroid containment bag. Using optical mining rather than electrically-driven mechanical equipment provides further mass savings. And by utilizing the water mined from the asteroid, there is no need to carry the propellant for the flight home and therefore no need for propellant tanks and associated hardware. Electrolysis equipment is used to split water into its constituents – hydrogen and oxygen – and cryocooling equipment allows these to be stored as liquids in heavily insulated tanks. Flexible tanks can be collapsed at launch, reducing the overall volume of the spacecraft and thereby the diameter of the fairing. They also simplify propellant management in zero-g. A scenario in which multiple asteroids are visited prior to returning home becomes feasible, because the spacecraft need not rely on supplies provided at launch, it can self-refuel. Furthermore, the same water can be used not only for the Omnivore Thruster but also for the attitude control system by using small electrically heated thrusters fed by a lithium battery.

These mass and volume savings would enable the spacecraft to be launched on a SpaceX Falcon 9 rocket, which itself offers significant savings in launch costs.[5] The optical mining method also maximizes the quantity of extracted resources measured in terms of the mass that the spacecraft can deliver per unit of payload launched. It has been estimated that over a lifespan of 10-15 years, one single unit will be able to undertake at least three mining missions to asteroids up to 10 meters in diameter and return with a total of 400 tons of water ice. The system is exceedingly flexible; so much so, that if the water were not the principal concern, a HoneyBee would still be able to return with a bag of raw material (or slag) which could then be exploited for space-based manufacturing of goods for terrestrial consumption or for construction of orbital infrastructure. In this case, the yield over the lifetime of a spacecraft would be 300 tons of water and 1,000 tons of slag.

A somewhat more sophisticated spacecraft has been proposed by Astrotecture, a space architecture consultancy, under another NASA NIAC contract. Called Rapid Asteroid Prospector (RAP), this consists of a 40-meter-long, 3-meter-wide graphite composite truss structure that has a water-based solar thermal engine at one end and, at the other end, a containment vessel capable of housing an asteroid up to 20 meters in diameter. The central section can accommodate various systems such as propellant tanks, water storage tanks, equipment for attitude control, communications antennas, and solar panels. The containment bag is conceived as a rigid enclosure whose shape is maintained by a series of inflatable ribs and truss members. The forward dome is designed to hinge open during asteroid capture. The intention is to use optical mining for extraction of volatiles, with concentrated sunlight provided by the same two large inflatable parabolic reflectors that will be used by a solar thermal rocket to thrust the vehicle to the asteroid. However, if the target asteroid is deemed inappropriate for optical mining, an alternative scheme would see robotic arms holding in position an auger to dig a deep hole. Once the auger had a load of frozen regolith, it would be withdrawn into a reactor where an electrical heater would recover the water from the icy soil. As in the case of the HoneyBee, the recovered water doubles as propellant for the solar thermal rocket on the return home, or the journey to another target. This spacecraft is meant to be capable of flying a number of missions by exploiting ease of serviceability upon returning home. Its modularity will be able to accommodate different configurations such as the addition of propellant and water storage tanks.

Both the APIS and RAP architectures have introduced us to the issue of capturing and stabilizing an asteroid for mining operations. This might prove difficult, as most such bodies rotate, sometimes on more than one axis and with high rotational rates. In science fiction, a spacecraft anchors itself to the asteroid and then uses its thruster system to arrest the rotation. Although technically feasible, even a small

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[5] More on this in Chapter 7.

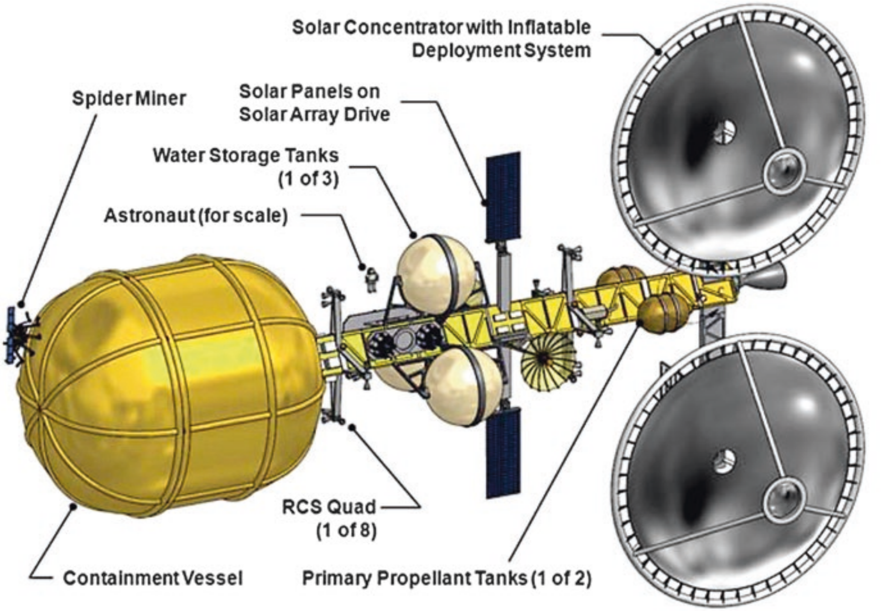

Figure 3.21 The reference configuration for the RAP spacecraft.

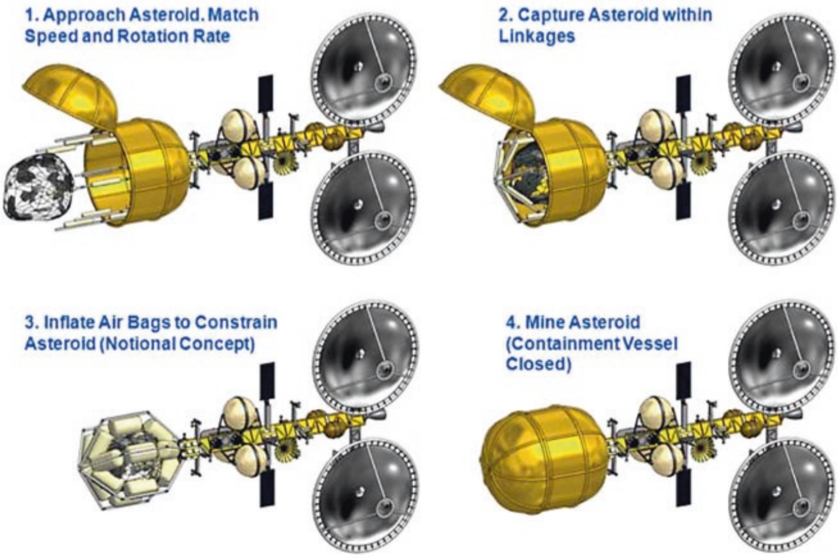

Figure 3.22 The RAP strategy for asteroid capture.

asteroid in a slow rotation on a single axis would require a large mass of propellant, all of which would have to be aboard the spacecraft at arrival.

In the case of RAP, the containment vessel will have mechanical arms that wrap around the asteroid. A number of airbags mounted on the arms will be inflated. The angular momentum of the asteroid will be canceled by rubbing the bags against the surface. Finally, the mechanical arms and airbags will tighten to secure the asteroid during mining operations.

The space engineering firm Tethers Unlimited, Inc., which began as a partnership between Dr. Robert P. Hoyt and Dr. Robert L. Forward, has proposed Weightless Rendezvous and Net Grapple to Limit Excess Rotation (WRANGLER). This has a deployable bag or net called GRASP (Grapple, Retrieve, And Secure Payload) and a lightweight tether system to attach to an asteroid. Lightweight, temporary inflatable tubes in the GRASP will expand the net prior to its being drawn around the asteroid and cinching down to provide a secure connection.

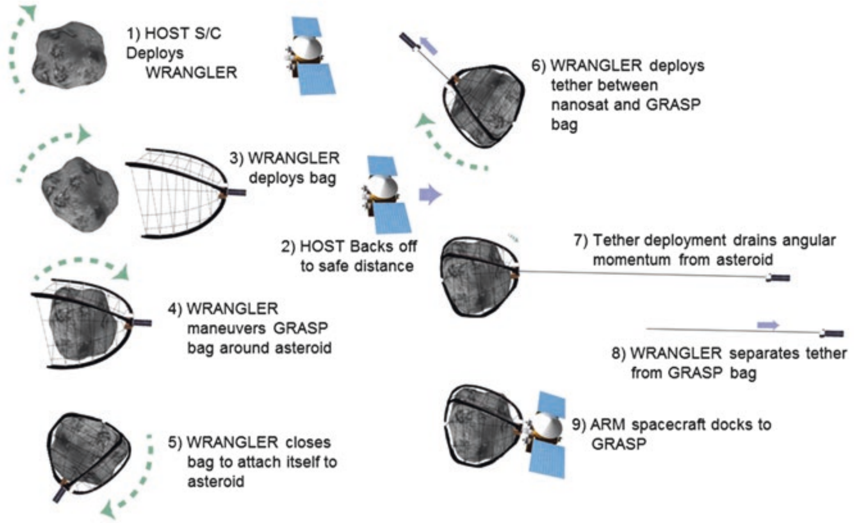

Figure 3.23 The WRANGLER concept of operation.

The system then deploys a high-strength lightweight tether that is kept in tension by an appropriate control system. Because the angular momentum remains constant, the deployment of the tether greatly increases the moment of inertia, which depends on the square of the tether length. By increasing the moment of inertia, the angular velocity is reduced. The asteroid is de-spun and de-tumbled. The main virtue of such an apparatus is that it reduces the complexity and mass of a spacecraft whose purpose is mining. That is, during the de-spinning operation it will not endure the dynamic loads that are imposed on a spacecraft in close contact. Flimsy components such as solar panels, antennas, and reflectors will not require either to be stowed or designed to endure additional stresses. The structure of the mining spacecraft, and its onboard systems, can be lighter and more durable. Using a tether also eliminates the need for the vehicle to operate in close proximity to the potentially dangerous spinning and/or tumbling asteroid.

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IMAGE LINKS

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4

Processing of Space Resources

BENEFICIATION OF SPACE RESOURCES

At the beginning of the previous chapter, we established that mineral beneficiation or dressing is a fundamental step in the processing of the raw material extracted from a mining site. Therefore, any plan to develop a mining capability in space must account for this task in the analysis and design of equipment and processing plants. Why? Consider what happens when an asteroid hits the surface of the Moon. A large amount of kinetic energy is transferred into the target surface in the form of shock waves. Depending on the mass of the projectile and its velocity, and on the geology of the target surface, the shock waves might create sufficient thermal energy to melt the local surface. Droplets of molten material will be ejected radially and upwards from the impact site and drawn back by gravity. On landing, they will weld with substances they touch, rapidly cool and leave complex mineralogical structures on the surface that are known as agglutinates. These are nothing more than collections of random surface particles glued together by the glass that had melted following the impact. Thus, even though agglutinates might contain one or more resource(s) of interest, their liberation might prove impractical unless they are beneficiated to simplify the unlocking of their contents in the refining process.

In Chapter 2 we learned that the presence of natural concentrations of industrially viable minerals (ore bodies) results from differentiating processes such as the aqueous concentration of crustal minerals, surface weathering of rocks, advanced fractionation of igneous rocks, and tectonic recycling of crustal plate.[1] There is no

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[1] As a reminder, igneous rocks are formed when magma or lava cools and solidifies.

D. Sivolella, *Space Mining and Manufacturing*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-30881-0_4

evidence of these processes on the Moon, and less so on most of the asteroids.[2] Once again, therefore, beneficiation will be necessary to reduce the raw material to a concentrate of particles of sizes suitable for efficient chemical resource recovery.

The complexity of operating in space provides an additional motivation for mineral beneficiation, in particular when appraising the logistics of such an undertaking. As we shall see in Chapter 7, one can envision a paradigm where raw materials are mined on the Moon and then orbital factories manufacture goods for terrestrial consumption. Given the cost, in terms of propellant, required to transport a payload from the lunar surface into orbit, it will be desirable to minimize the proportion of unusable material. Therefore beneficiating will permit shipping into orbit only the material that has been refined. As we will learn later in this chapter, several resource recovery processes require one or more reagent(s) for producing oxygen, metals, and other resources from lunar or asteroidal material. Treating raw material to reduce it to a fine agglomerate will minimize the reagents utilized, and also the propellant required to deliver them to the processing plant. Indeed, processing an already beneficiated agglomerate will ease the recovery of reagents, since less unwanted residual material needs to be withdrawn from the reagent.

Lunar Mineral Beneficiation

In the absence of a lunar mining industry, we are once again forced to adopt terrestrial processes and equipment that can be adapted to the space environment. In the previous chapter, it was explained that mineral beneficiation starts with crushing, screening and grinding until an agglomerate of fine particles is produced. Lack of air and water will not adversely affect these steps. They can take place in either ‘dry’ or ‘wet’ conditions, although ‘dry’ processing will mean greater equipment wear, a more significant power consumption, and a reduction in capacity. This implies a higher cost, as more mass has to be transported on the surface (or manufactured) and maintenance must be scheduled more frequently. We should seek to employ mining methods which help to reduce the burden on these beneficiation steps.

One such solution would be to induce a thermal shock into the rock to make it more friable, and hence much easier and faster to crush to an agglomerate of fine

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[2] As we saw in Chapter 2, the Moon has undergone a differentiating process that has caused the formation of a superficial crust enveloping a mantle and nucleus. And of course, differentiated asteroids such as the stony-iron and iron types do have a preferential concentration of specific minerals, either because they are the fragments of a much larger differentiated asteroid or because the energy of an impact with another asteroid produced sufficient thermal energy to trigger the differentiation process.

particles. This could be achieved by powerful laser beams, by optical mining, or by exposing the material to a high temperature and then showering it in a cryogenic fluid such as liquid oxygen. A high temperature followed by instantaneous cryogenic cooling will wreak havoc with the strong chemical bonds peculiar to rock material, enabling it to crumble. Any of these methods could be applied during the extraction process, either working in concert with the main mining equipment or by being the mining extraction process itself. Conversely, they could be employed after material extraction if carried out at a separate location from the mining site. Use of cryogenic oxygen would surely be best suited as a standalone beneficiation process rather than as an aid to material extraction, given the need to recycle the fluid. It is not suitable for use on the exposed surface, as the liquid would swiftly flash to gas and escape. Laser beam or optical mining would be suitable for both surface and underground mining. The main difficulty is providing a continuous, reliable source of power. Optical mining, which needs sunlight, will not be possible during the fortnight-long lunar night unless it is performed at the rim of a polar crater where, except for a few days per year, there is uninterrupted sunlight. For underground mining, there would have to be an elaborate mirror/lens systems to direct sunlight to the mining face.[3]

On the other hand, the production of powerful laser beams necessitates an equally vigorous source of energy, and this means crossing into the territory of nuclear power and heavy-duty power cables. In Chapter 7, we shall survey some recent advances in the generation of nuclear energy for civilian applications and investigate how they can support the application of nuclear power in space.

Even if some of these processes can only be used in the preliminary crushing of the rock, they would offer greatly improved mineral beneficiation. In that case, the use of wet operations for subsequent crushing, screening, and grinding might prove feasible because of a reduction in the requirement for liquid.[4]

Once we have achieved an agglomerate of fine particles, the next step consists of producing a concentrate that will effectively undergo the resource recovery process. In other words, we need to discriminate between particles that have a meaningful amount of the desired resource(s) and those which are waste. On Earth, this is mostly done by using water and air as a medium to exploit the differences in particulate density. Given the scarcity of both on the Moon, and the fact that water is more attractive as a rocket propellant and as a human

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[3] This would resemble the typical mirror and lens apparatus of your run-of-the-mill Indiana Jones-style lost temple!

[4] As pointed out in Chapter 2, water is one of the most important resources that the Moon can offer, and in a later paragraph we will survey techniques to acquire it. Hence wet beneficiation will be possible to a certain extent. Of course, the less water we devote to mineral beneficiation, the better. We should seek beneficiation technology that reduces the inefficiencies of dry processes by using the least possible amount of water.

consumable, alternative methods will need to be developed; for example, based on gravity, magnetism, and electrostatics. Let us begin with the last one.

Generally speaking, electrostatic separation involves the interaction of an external electric field and the electric charge acquired by the particles (e.g., grains of regolith). This can occur by using three selective electrification processes: tribo-electrification, conductive induction, and electro-bombardment from heated cathodes in the vacuum of space in combination with a conductive discharge. Whereas tribo-electrification generates positively and negatively charged particles, the others yield particles of only one polarity. Because regolith has an average grain size of 45-100 microns, its powdery nature makes it an excellent candidate for this technique. In fact, it occurs naturally on the Moon. Optical observations and direct measurements have both shown that lunar dust migrates across the surface by means of a naturally occurring electrostatic driven motion, albeit a rather inefficient one. Industrial scale electrostatic separation is ideal for the airless, low temperature and low gravity lunar environment. Lack of air implies lack of moisture. This will not only prevent the material grains from sticking together, it will also removes the dielectric (insulating) behavior of air, enabling higher voltages to be applied between electrodes. The low gravity will reduce the speed of the particles and thereby enhance separation by allowing longer charging times.

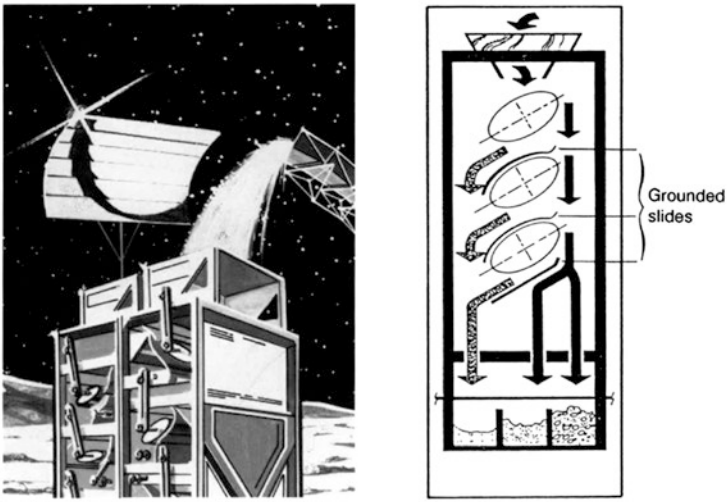

Figure 4.1 A schematic of a prospective separator on the lunar surface. The mirror at the top focuses solar radiation onto the soil to enhance the conductivity of the ilmenite by heating to about 100°C. The arrows show how the soil would separate under the effect of the electrodes (here shown as ellipses). The non-conducting material (e.g., agglutinates) collects at the far right, while the conducting and semiconducting material (e.g., ilmenite) accumulates at the far left.

As an example, consider electrostatic separation of ilmenite from agglutinates. As both include iron in their formulation, separation by magnetic means would not work. But within an electric field, ilmenite behaves like a semiconductor and the agglutinates serve as an insulator. This marked difference in electric behavior makes it possible to concentrate the ilmenite by means of electrostatics. One can envision a vertical free-fall tower fed with soil from the top. As the particles fall, high-voltage electrodes in the structure of the tower subject them to an electric field gradient in the direction of flow. Accurate positioning of the electrodes, in combination with the free-fall motion, will allow the ilmenite to be collected separately from the non-conductive agglutinates. To improve efficiency and speed up the process, especially in low gravity, the electric charge on the ilmenite can be intensified by heating the material to 100°C before it is poured into the tower. Heating will not affect the agglutinates. This amplified contrast in conductivity will boost the separability of the ilmenite from the rest of the material.

Because lunar soil is bound with naturally occurring iron/nickel metal particulates, magnetic beneficiation would be another viable option. A low magnetic field gradient could be used in a similar fashion to the electrodes of the electrostatic separator tower, this time to gather together particulates of similar magnetic strength. Perhaps a synergy of magnetic and electrostatic separation would optimize efficiency. For instance, metal particles could be first separated from the ilmenite and other soil components using magnetic separation. Then electrostatic separation could screen out such agglutinates as might have separated with the metal particles. This would refine the desired ilmenite and metal fractions. A multi-step process could use various stages of electrostatic and magnetic separation for optimal sorting and concentration.

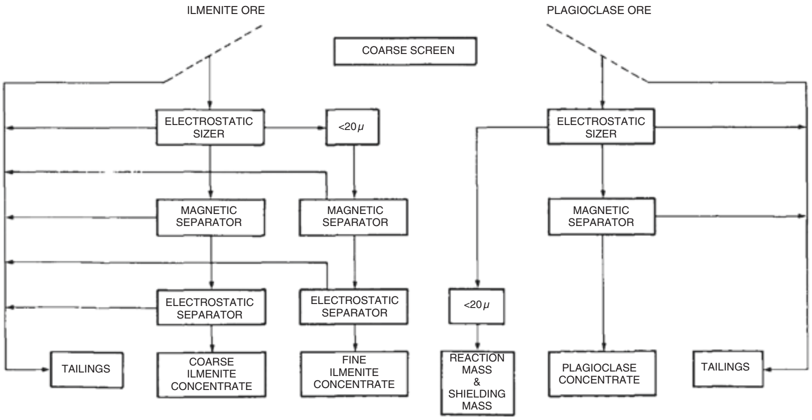

Figure 4.2 A schematic showing how electrostatic and magnetic separation could be arranged within a multi-step process for optimal sorting and concentration.

Beneficiation of Asteroidal Resources

Beneficiation will also apply to the extraction of raw materials from asteroids. In this case, it can occur before the mining spacecraft departs the asteroid, or during transit if the intention is to move the whole asteroid towards Earth. A third option entails waiting until the asteroid has been delivered to an orbital processing plant. The preferred option is likely to be in-situ beneficiation, because returning a smaller mass will minimize the propellant for the trip. As noted in Chapter 3, the unwanted material that is isolated by a preliminary beneficiation prior to departure, or in transit, could be used as propellant for a rocket or a mass driver-type rocket.[5] For crushing and sizing, a rotating cylinder housing a rocking jaw for coarse crushing and a series of rollers for fine crushing could be employed. By arranging the crushing elements in a radial pattern, the rotation of the cylinder will generate a centrifugal acceleration from the hub (input) to the rim (output) where it will be possible to collect fine powder with an average size grain of 0.2 mm, ideal for metal extraction. At this point, particles of metal and volatiles such as water, carbon dioxide, and methane can each undergo a distinct separation process.

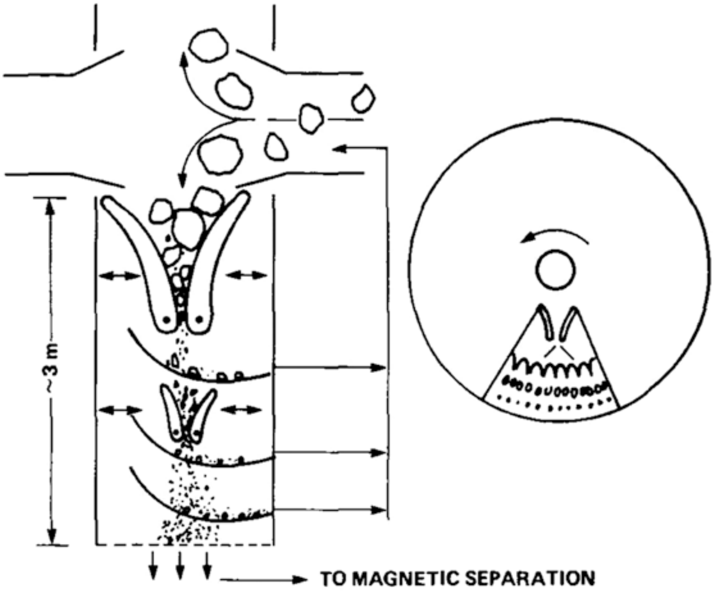

Figure 4.3 A schematic of a prospective crusher of asteroidal material using a drum with a diameter of 3 meters that spins at 10 rpm.

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[5] A mass driver rocket engine develops thrust by expelling pieces of material by means of an electromagnetic catapult. The reaction against the coils of the electromagnetic catapult propels the spacecraft forward.

Volatiles can be recovered by heating crushed material to a temperature appropriate for the desired resource. Water will start to release near 100°C and continue until about 400°C. Carbon dioxide is produced by the dissociation of hydrocarbon compounds and by the reaction of elemental carbon with an oxide phase. Hydrocarbons break down or volatilize in the range 100-700°C, releasing a variety of compounds such as methane and petroleum vapors. A possible recovery scheme would consist of a heat-exchanger positioned at the focus of a sunlight collecting mirror. The material would linger in the heat exchanger for the time necessary to attain the proper temperature. Then a cyclonic separator (resembling that of a floor hoover) would set the dust apart from the volatiles because dust settles rapidly to the outer wall of a curved conduit. The volatiles would proceed to a shaded heat exchanger for condensation and storage in a tank. The system has a number of drawbacks: large mirrors and devices, and a large radiator to dissipate the heat of condensation. Inflatable technology might be of great help by providing a low-cost and low-volume (in terms of launch and the outbound trip) option, as we saw with the APIS and RAP spacecraft in the preceding chapter. For the heat exchanger to condense the volatiles, a double condenser might be preferable. The first tank would operate at an absolute temperature close to 250 K and precipitate most of the water and hydrocarbons. The second tank would be 100 degrees warmer and operate at a slightly higher pressure to condense the remaining water and carbon dioxide vapors. The dust could be pressed into molds to make reasonably solid pellets for use by a reaction mass engine such as one modeled on the APIS Omnivore Thruster.

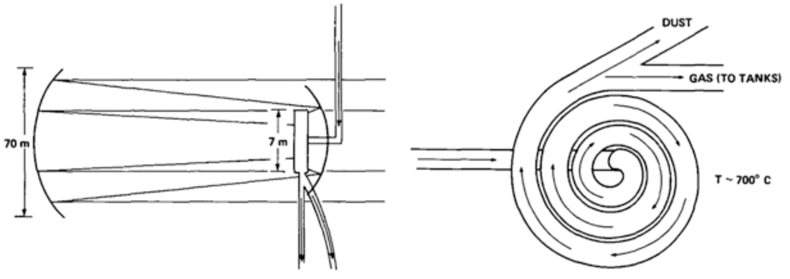

Figure 4.4 A schematic of a prospective high-temperature apparatus for extracting volatiles from asteroidal material. To the left is the heat exchanger positioned at the focus of a sunlight-collecting mirror, and to the right is the cyclone that separates volatiles from the dust.

To extract and remove metal, a low-pressure carrier gas can transport the crushed material through a magnetic or electric field, where the sorting takes place in a similar manner to that shown for magnetic and electrostatic separation of lunar material. The enriched fraction (consisting of metal and sand) would be delivered to a storage tank. Further processing and resource recovery would likely occur at the processing plant at the destination, since it would not be sensible to ferry the mass of that apparatus to the asteroid and back.

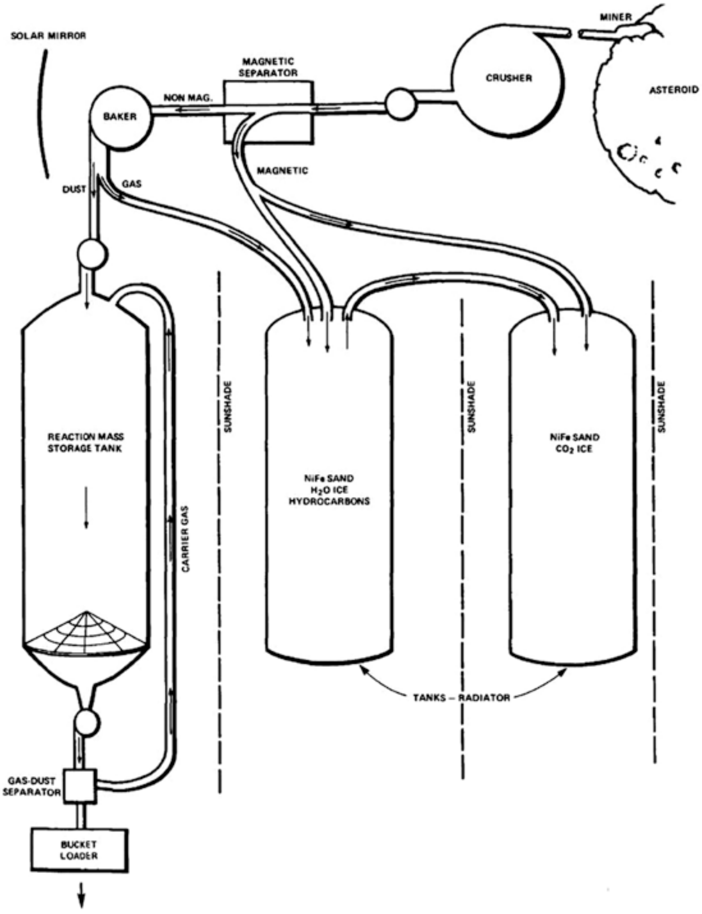

Figure 4.5 A schematic showing the layout of a preliminary beneficiation apparatus for asteroid mining.

REFINING OF SPACE RESOURCES

With lunar or asteroidal feedstock reduced to an agglomerate of appropriate size, the next step is to extract the resources outlined in Chapter 2. The technical literature offers many suggestions for possible processes, and there have been many experiments using simulants. It is not the purpose of this book to review the existing literature, so we shall discuss only a small number of representative examples.

Generally speaking, the development of a resource recovery method must consider the low-gravity, high-vacuum environment of space and limiting factors such as there being only limited supplies of water, air, and chemical reagents. Apparatus must not only be capable of surviving the aggressive environment of chemical reactions but also the hostile environment of space. Ideally, a recovery process will require the least start-up quantities of chemical reagents and oxidizers, minimize their losses, and optimally recycle them.

The Fusion Torch

Plasma from a fusion facility could be used as a torch for digging by vaporizing and ionizing the rock. The ionized ore will flow through a transverse electric field in much the same way as occurs in a mass spectrometer, and the ions will follow specific paths depending on their atomic mass and electric charge. This rather simple method would skip the beneficiation process by producing streams of separated materials ready to be condensed, collected, and solidified for shipping or (if necessary) further purification. Such a system has the enviable advantage of being essentially 100% efficient because the plasma would be tapped directly from the reactor, eliminating the requirement for conversion cycles. The only drawback might be a large radiator to dissipate the heat to space, as water for cooling might not be available in the necessary quantities. A fusion torch could be designed to melt the rock rather than to vaporize it. Then an electric or magnetic field could separate the melt into its constituents. In fact, experiments have shown that migration in the molten state should be much faster than the migration rates in solids. Considering that lunar material is largely silica, melting will take place in the range 1,500-2,500°C. This method would therefore be straightforward to develop and operate.

Solar Furnaces

Solar furnaces can separate some elements from molten materials based solely on their volatility. They can attain temperatures as high as 3,500°C. Heating typical lunar rocks to 2,000°C will see sodium and potassium evaporate, followed by silicon and iron. The leftovers would be a mixture of calcium, aluminum, magnesium, and titanium. Further processing can extract these metals as well. Solar furnaces are strongly recommended for space applications, because they are simple and can generate high temperatures and heating rates. Each square meter of a solar collector on the Moon or in near-Earth space could provide around a kilowatt of thermal power. A reflector of 30 square meters with a mass of only several kilograms could collect over a million watts of solar power. If solar arrays provided this same amount of energy, they would cover an area five times larger. Of course, there needs to be the equipment to regulate and condition this power. If a high number of megawatts must be generated then it would be better to use other processes than solar cell arrays. However, this method would work equally well on the lunar surface and for orbital plants that process asteroidal material.

We can conceptualize a facility in which the particle feedstock is dispensed from a hopper into a multi-chamber furnace that rotates from the hopper position to the focus of the solar concentrator. As the furnace rotates, the chamber of feedstock is sealed to prevent the extracted gases from escaping. The beam from the solar concentrator enters the chamber through a window, and thermal energy vaporizes and dissociates (ionizes) the vapor to make a plasma. An electrostatic separator similar to that used in the fusion torch can then manipulate and separate the ionized species according to their mass and charge. If the feedstock is rich in oxygen, the electrostatic field will not influence the neutral oxygen.[6] It can continue to flow downstream for liquefaction and storage into tanks (either rigid or inflatable, as desired) that are shaded from sunlight and shielded from micrometeoroid strikes. If any residue is left (slag), it can be removed for further processing or dumping (as appropriate). Although this process is energy intensive, this requirement can be mitigated by adopting an efficient design of the solar concentrator, by recovering heat from the slag, and by using the waste heat of other apparatus at the processing plant to preheat the feedstock.

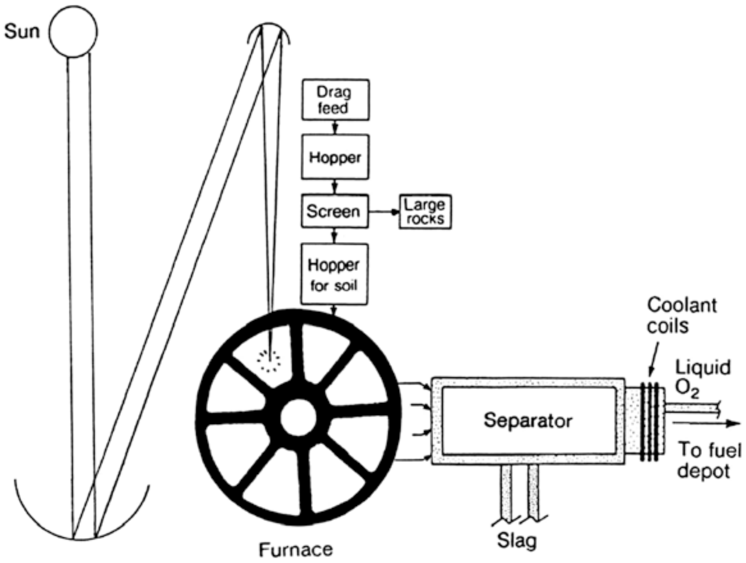

Figure 4.6 A conceptual solar furnace facility.

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[6] Oxygen does not ionise, so it is not captured by the electrostatic field.

Vacuum Fractional Distillation and Differential Melting

Fractional distillation is a mature terrestrial process widely employed by oil refineries, petrochemical and chemical plants, natural gas processing, and chemical industries, to name a few. At the heart of a typical apparatus is the so-called fractional or distillation tower. This is a tall vertical column in which liquid and vapor are in intimate contact for efficient transfer of mass between the two phases. Generally speaking, fractional distillation is a physical process whereby a mixture is separated into its components or fractions by exploiting the differences in volatility of its components.

Typically, a pool of chemicals in a liquid state at the bottom of the tower is brought to the boil by means of a heat exchanger acting as a reboiler. The vapors flow upwards towards the top of the tower, and in doing so experience a thermal gradient in which the temperature decreases with distance from the reboiler. As the vapor rises from the bottom the thermal gradient prompts the less volatile components to condense, leaving the most volatile ones to continue to the top. Vapor condensation occurs on perforated trays (also known as sieve tray plates) that are conveniently arranged along the tower's length. A tray can retain a pool of liquid that is 10-20 cm deep. The liquid is prevented from weeping through the holes by a steady stream of vapor pushing upward from the boiling liquid on the plate immediately below. As the vapor bubbles through the pool of liquid it condenses, releasing heat which vaporizes an equivalent amount of liquid. As this vapor rises, it bubbles through the next plate up. And so on. The level of liquid at any given plate is maintained by a lip or weir. Any overflow spills through a passage, known as a downcomer, that returns the liquid to the plate immediately below and it is designed to prevent it from flowing back to the plate of origin. The liquid on each tray will be characterized by a specific composition that is a subset of the mixture that was introduced into the tower.

The raw material (in a liquid state) that is to be distilled is introduced into the tower at a plate whose liquid matches that composition. The liquid descends across the trays until it reaches the bottom, where it is heated by the reboiler. The resulting heat transfer from tray to tray causes the liquid with the lowest boiling point to vaporize and move up the column, as the rest flows countercurrent down the column. Purification is thus achieved by the separation of the components with different boiling points. Insulation is critical because the energy for vaporizing the liquid on a plate is obtained from the condensing vapors. Any heat loss will hinder the desired interplay between the liquid and vapor phases.

At the top of the column is an overhead condenser that converts the enriched vapor effluent into a liquid, with the resulting heat being released into the environment. A portion of this liquid is tapped off as 'head' product. The balance is returned to the top of the column as reflux. The ratio between the amount of liquid that is returned and the amount tapped off is an important quantity in the design of the distillation process, as it allows for a more complete separation of products. As the reflux is fed from the top of the tower, its fall to the bottom provides the cooling required to condense the vapor that is flowing upwards, thereby increasing the effectiveness of the tower. Distillation towers also have outlets along their length at which to withdraw specific fractions of chemicals distilled from the original feed of raw material. These outlets are positioned at the perforated tray whose liquid has a composition which contains the fraction of interest.

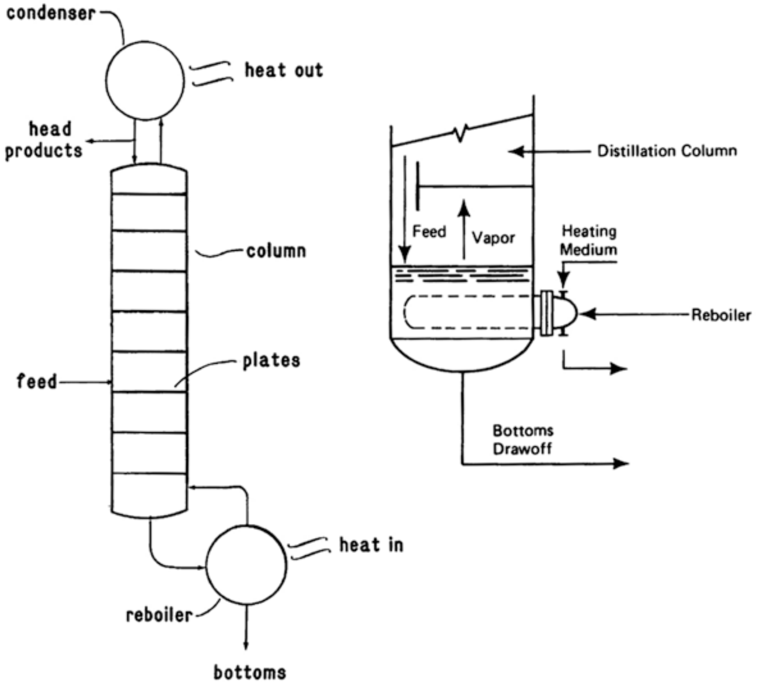

Figure 4.7 A schematic for a distillation tower.

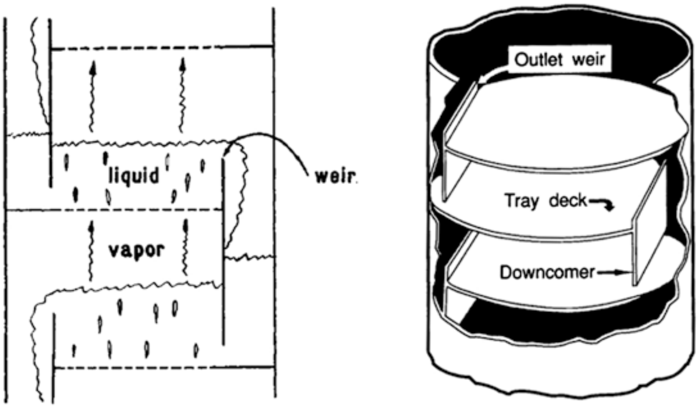

Figure 4.8 A cross-section of a column with sieve tray plates (left) and the tray locations inside a distillation column (right).

This process could readily be adapted for the Moon by taking into account the low gravity and exploiting the low temperatures. In fact, the column pressure is specified by the lowest temperature available in the overhead condenser. In a lunar environment this will correspond to as low a column pressure as desired. By radiation into space, it will be rather straightforward to reduce the temperature inside the column to cryogenic levels to achieve a near-vacuum condition that will help to reduce the boiling point and increase the vaporization rate. Once the material has been vaporized, those constituents of interest will be condensed and recovered. The unwanted mineral vapors will simply be vented to the lunar vacuum.

Fractional distillation is one of the few terrestrial process that could be adopted for the Moon at basically face value, with only simple modifications to allow for the low gravity. It uses apparatus whose behavior is well-known, and is resilient to damage or incorrect operation. It relies on the production of a large amount of heat, rather than on shaft and electrical power. On the Moon, heat can easily be arranged by focusing solar energy, a nuclear power source, or simply by tapping the waste heat produced by the processing plant or outpost. In this way, electrical energy can be saved for equipment that cannot do without it. The process is also suitable for an orbiting processing plant that refines asteroidal material, providing a section of the processing plant was spun to create the necessary sense of gravity.

A similar but simpler process is based on differential melting. This is a multi-stage approach where the ore mixture is successively heated at a higher temperature to allow the melting and separation of individual ores. This exploits the fact that every mineral has its own melting point. For a given temperature, only that specific mineral will melt. By repeating the process, the components can be separated from the mixture. But this is less effective than fractional distillation because the individual melts will inevitably be contaminated with partially dissolved other minerals.

Water and Oxygen Recovery

One of the first resources to be mined on the Moon will undoubtedly be water, given its ubiquitous role in the preparation of cryogenic propellants (hydrogen and oxygen), as a propellant itself, as a constituent of mineral dressing and refining processes, and as a fundamental requirement for human survival in an extraterrestrial outpost. As we saw in Chapter 2, observations by orbiters such as Clementine, Lunar Reconnaissance Orbiter, and LCROSS have given ample evidence of there being water ice in craters in the polar regions of the Moon whose floors are in permanent shadow.[7] It appears that approximately 6,000-15,000

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[7] It is good to recall that physics forbids water in any other region of the Moon. In fact, the vacuum of space and the intense heating to which the surface is subject for 14 days at a time force any trace of water embedded in the soil to sublimate and permanently escape the weak gravity.

square kilometers at the south pole bear water. There is less water-bearing surface at the north pole, but it is present in greater concentrations. Since the temperature might never rise above 100 K in these areas, it is likely that the water has been accumulating for billions of years.

Extraction of water is reasonably straightforward, at least in concept. All it takes is a means of excavating the site with adequate machinery and then transporting the load to an extraction plant where the dirt is warmed to release its water content. This water vapor can be condensed into ice blocks, then melted for storage in tanks. The full tanks can be transferred to an electrolysis plant located in proximity to the rim of the shadow crater to collect the solar energy for the electrolysis that will split the water into oxygen and hydrogen. An alternative to sunlight is nuclear power. In fact, this might be better because it recognizes the fact no site is completely free of brief periods of darkness.

At other sites on the Moon, oxygen can be extracted from regolith and, if required for propulsion, it can be used in conjunction with hydrogen brought from Earth. One way of doing this is by operating a hydrogen reduction system based on the principle of reducing metal oxides commonly found in the regolith, for example in the rich iron-bearing ilmenite, olivine, pyroxene, and glass. The process consists of heating at high temperature (1,200-1,300 K) regolith feedstock bathed in gaseous hydrogen to release oxygen from the oxides. The liberated oxygen combines with the hydrogen to produce water. This can be split into oxygen and hydrogen by electrolysis. The hydrogen is sent to a condenser to remove any residue of water, which is then routed to the electrolyzer. The dry hydrogen is then recirculated to the reactor. Naturally, some hydrogen will be lost by the process, but it will probably be recovered, at least in part, by outgassing of hydrogen of the solar wind that penetrates the regolith. The oxygen is dried to reduce the water content and finally is liquefied and sent to the storage tanks. Both heating the regolith and the electrolyzing of water are expensive in energetic terms. A solar furnace would be enough to heat the regolith, but the decomposition of the water would require a nuclear reactor or a broad solar cell array. The process leaves a mixture rich in metals that can undergo processing to recover those elements. For instance, for each liberated oxygen atom a molecule of ilmenite also discharges metallic iron and titanium dioxide, the latter being in the form of a mineral known as rutile.

Regolith that is rich in silicates can be another source of oxygen, if a carbonaceous high-temperature (carbothermal) reduction process is used. The regolith feedstock is contained in a methane-filled reaction chamber. A beam of concentrated solar energy locally melts the regolith to a temperature sufficient to crack the methane into carbon and hydrogen. While the hydrogen stays in the chamber, the carbon diffuses into the molten regolith and reduces the oxides in the melt, turning into carbon monoxide. The carbon monoxide and the hydrogen are both

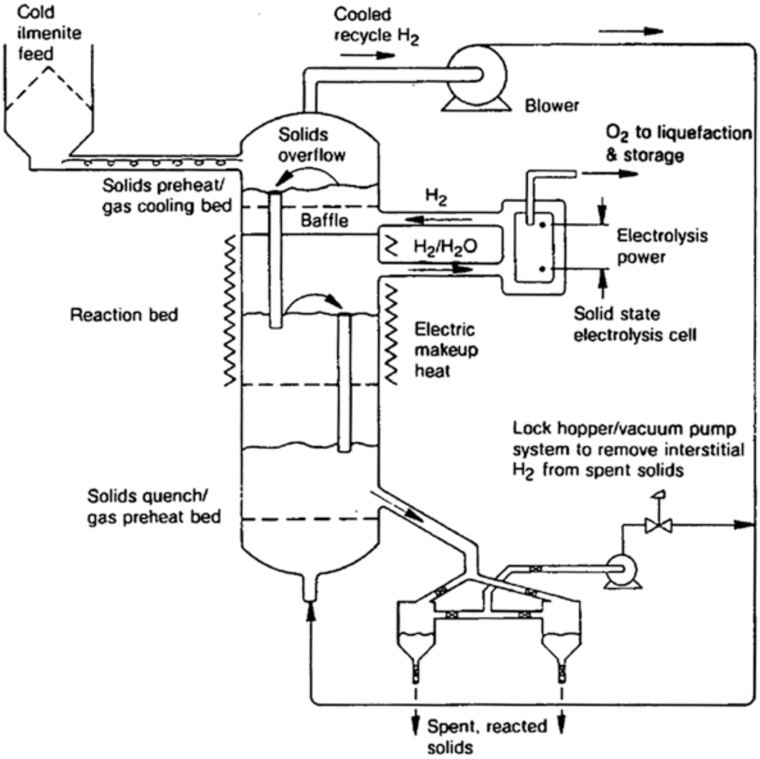

Figure 4.9 A high-level schematic of a processing plant for extrating oxgyen by hydrogen reduction of ilmenite.

pumped out of the chamber and combined into a catalytic reactor to produce water and methane. The former is routed to the usual electrolyzer reactor. The latter returns to the reaction chamber where the carbothermal reduction process can start again by heating either a new area of the feedstock or a new load of regolith. The oxygen and the hydrogen from the electrolysis process require to be purified of water, because they are produced in the gaseous form and will inevitably contain some water. The dried hydrogen is routed back to the catalytic reactor, where it combines with carbon monoxide. The dried oxygen is then liquefied and stored. The process is extremely challenging from materials, thermal, optical, and chemical points of view. However, one advantage is that the same method can also be used to produce silicon, iron, and ceramic materials.

Another way to obtain oxygen from regolith is by undertaking the lunar magma electrolysis process. As the name implies, electrolysis is carried out on regolith melted in a furnace, rather than on water. The cathode will get plated with an iron-rich metal alloy and the anode will liberate gaseous oxygen, which can be liquefied for storage. The residue accumulated on the cathode can later be removed and further elaborated to extract elements of economic and industrial interest: iron, chromium, manganese, titanium, silicon, etc. This scheme uses a lot of energy, and for that reason it has to rely either on a nuclear or solar power supply. Compared to the hydrogen reduction process, it is more energy-hungry because it operates at a much higher temperature, it requires the handling of molted regolith, and it is less efficient. On the other hand, the cathode accumulates a metal and silicon residue from which valuable products can be extracted by fractional vacuum distillation or a plasma torch.

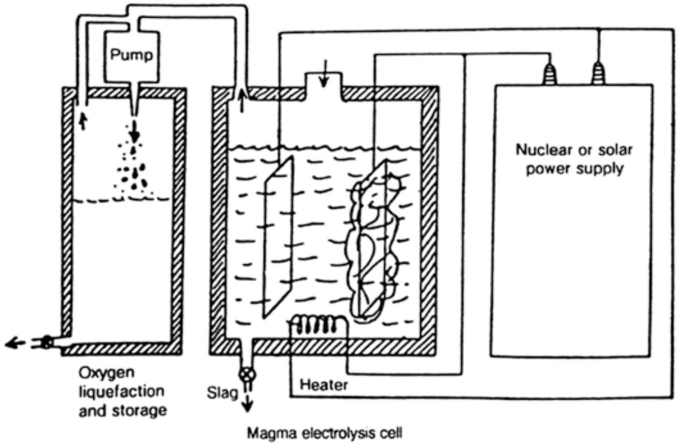

Figure 4.10 A high-level schematic of the magma electrolysis process. Note how at the anode (left plate) oxygen leaves the cell for liquefaction and storage, while a residual rich in iron, titanium, magnesium and chromium accumulates on the surface of the cathode (right plate).

Metal Recovery

Metallurgy, the art and science of economically concentrating, extracting, refining, and fabricating metals and alloys is thousands of years old. With experience, the extraction of metals was developed into pyrometallurgy, electrometallurgy, and hydrometallurgy. Each of these processes relies on a different driving force or mechanism for reducing the combined metal to its pure form.

Pyrometallurgy uses high temperatures to drive a chemical reaction. The obvious disadvantage is that high temperatures require a large amount of energy and containers that can withstand the thermal stress. Electrometallurgy is based on a driving force of an electrical nature, such as the aluminum refining explained elsewhere in this chapter. Hydrometallurgy relies on the solubility of certain minerals in aqueous solutions, such as sulfuric acid. Once dissolved, the ions of metal can be recovered by low-temperature electrolysis, precipitation, chemical reduction,

ion exchange, or solvent extraction. It is clear that space-borne metallurgical processes will mostly rely on the first two types, because solar energy for running furnaces and power plants will be readily available, whereas water will not.

Metal production on the Moon could use the Mond scheme, a process invented by Ludwig Mond to extract and purify iron alloys. This is a gaseous carbonyl process. In fact, carbon monoxide gas is heated to 100-200°C and introduced at a pressure ranging from 10-100 atmospheres to react with metals in the regolith (metallic iron, nickel and other metals) and make gaseous compounds with the generic name of carbonyls. The carbonyls can be liquefied at room temperature with a vapor pressure similar to that of water. By distillation or selective decomposition of the gaseous carbonyls at normal atmospheric pressure and a temperature of 200-300°C, extremely pure iron and nickel can be obtained. The carbon monoxide released during decomposition can be recycled. A purity of 99.97% can be achieved by a single step. This is a simple process needing only a modest amount of energy because it requires heating at temperatures no higher than 120°C to volatilize metal and 300°C to deposit metal. Furthermore, since the main reactants are in gaseous form, it is fairly simple to cycle and reuse the heat used by the process. The Mond process works best when applied to native metals, rather than ores or complex minerals. Pure iron with less than 10% of contaminants could be collected using a magnetic rake ploughing the lunar surface. The process could also be employed to further process the leftovers from the extraction of oxygen in the hydrogen reduction of ilmenite. In this case, iron can be obtained in a single step that leaves pure titanium dioxide as a by-product, which is a good starting point for the production of titanium. The residue of molten silicates that accumulates on the cathode during electrolysis can be processed in this way to yield iron, manganese, chromium, nickel, and cobalt. Once again, and depending on the composition of the regolith, titanium or silicon can be left for further processing.

Another means of recovering iron and titanium is to react ilmenite with carbon and chlorine (carbochlorination) at 800°C in a fluidized bed reactor. The result is gaseous iron chloride ($FeCl_3$), carbon dioxide (CO), and titanium dioxide (TiO_2) in the form of titania. The $FeCl_3$ gas is condensed and then reacted with oxygen gas at 300-350°C in a second fluidized bed to produce Fe_2O_3. This is then reduced with either carbon or hydrogen gas below 1,000°C to produce low-carbon steel or pure iron. The CO or H_2O formed is recycled to recover the oxygen. An alternative is to reduce the $FeCl_3$ directly to metallic iron with hydrogen at 700°C. The TiO_2 can be processed to recover titanium metal. Since titanium forms a highly stable oxide, it cannot be reduced with carbon or hydrogen. It can be reduced with calcium metal. A process has been developed for this reduction in which pelletized Ti_2O and calcium metal powders are heated at 925-950°C for several hours. The CaO is preferentially dissolved by acid leaching. Disadvantages are that the acid and water must be recycled. The calcium metal could be obtained by processing anorthite ($CaAl_2Si_2O_8$) to extract its aluminum.

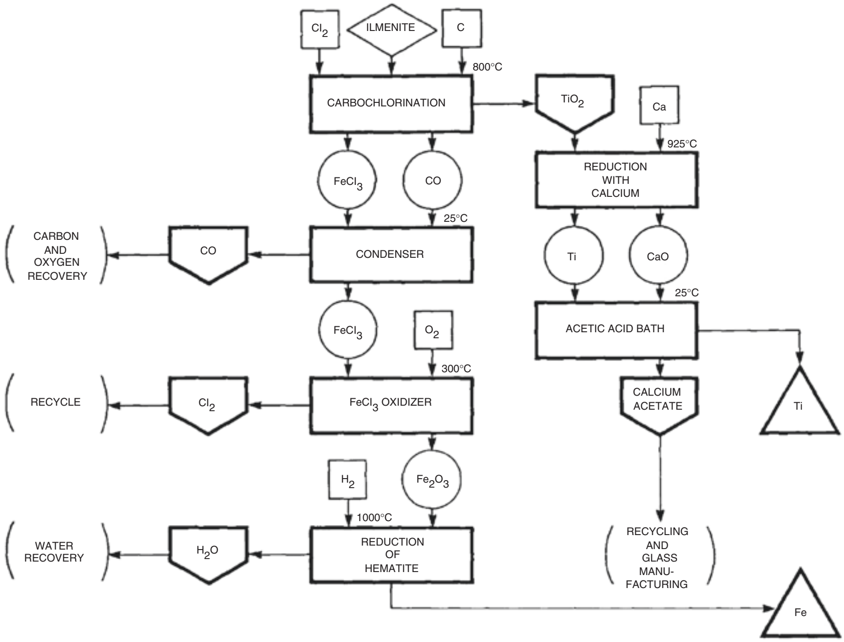

Figure 4.11 A flowchart of iron and titanium processing from ilmenite.

As anorthite contains abundant aluminum, a silicon reduction produces aluminum oxide (Al_2O_3). This can be decomposed by electrolysis to obtain oxygen and metallic aluminum. Part of this aluminum is fed back into the silicon reduction phase, where it participates in the reaction. The reaction also produces an aluminum-silicon alloy that is suitable for casting into structural beams. This process offers the advantage of being able to obtain elemental silicon, elemental aluminum, and casting alloys of silicon and aluminum with low melting temperatures. Furthermore, if appropriate sites in the lunar highlands are chosen it can use most of the soil or rock as feedstock. The disadvantage is that it needs some feedstock beneficiation to eliminate most of the iron-rich minerals. Also, it requires inert electrodes that will not dissolve in the molten flux. However, the technology can borrow heavily from the aluminum-producing industry on Earth.

A bipolar electrolytic cell can be used as the starting point for recovering oxygen and metal from lunar ore, whether unbeneficiated or mechanically reduced to dust. Ore is fed into the cell, where an electric current flows from a terminal anode to a terminal cathode passing through numerous bipolar plates. The top surface of each bipolar plate operates as a cathode and the bottom surface as an anode. The alumina (Al_2O_3), silica (SiO_2), ferrous oxide (FeO), and titania (TiO_2) content is electrolyzed to form oxygen at each anode and an aluminum, silicon, iron, and

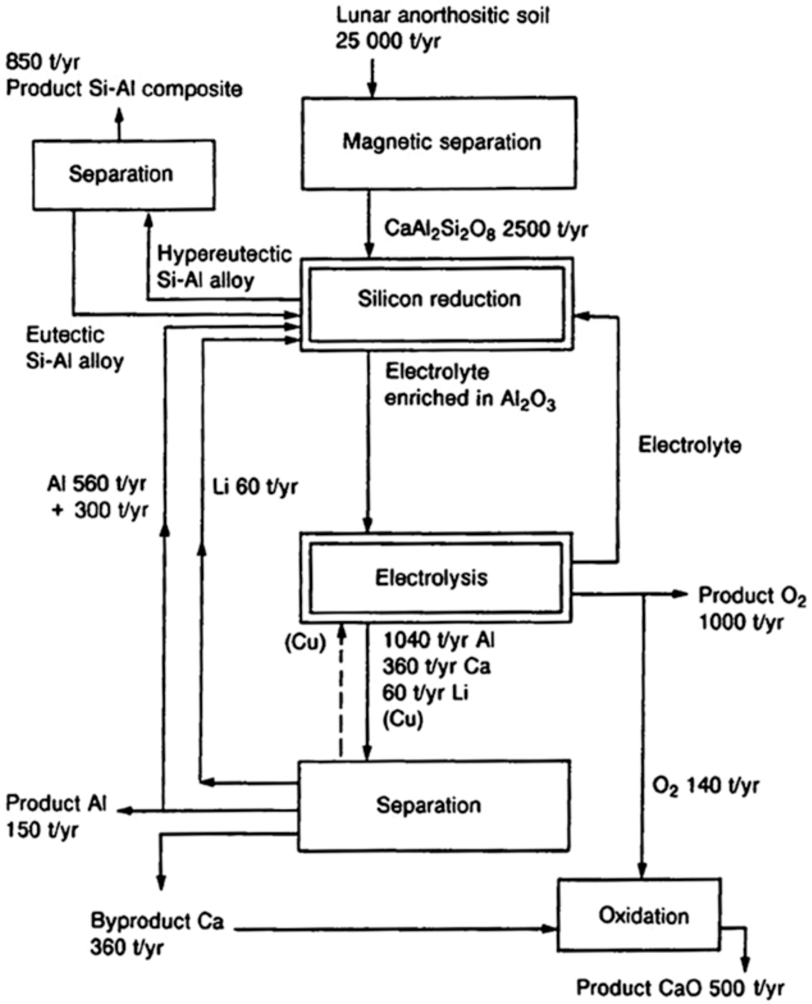

Figure 4.12 A schematic for a process to obtain oxygen, aluminum, and calcium from lunar anorthite.

titanium alloy at each cathode. The oxygen gas rises from each anode through the electrolyte to provide circulation of the electrolyte, then depart the cell at the top. The metal alloy that settles at the bottom is tapped periodically and fed to a vacuum fraction distillery which extracts the individual elements. As the reaction proceeds in the cell, calcium and magnesium accumulate in the electrolyte. After being removed, they are sent to another vacuum fraction distillery for recovery of the individual elements.

Another method for metal extraction that is popular in the technical literature calls for leaching by hydrofluoric (HF) acid. Low-temperature hydrochemical

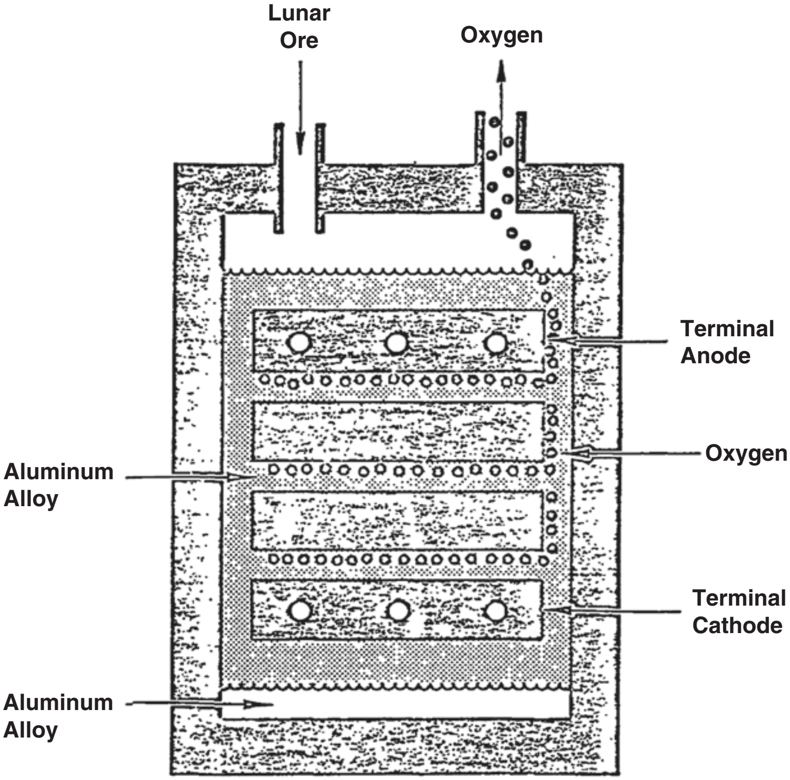

Figure 4.13 A schematic for a bipolar electrolytic cell to obtain oxygen and metals from lunar ore.

steps separate the silica content of the feedstock from metallic oxides in minerals by converting them to fluoride and fluorosilicates. Vaporizing the silica (as SiF_4) leaves fluoro-based salts of calcium, aluminum, iron, magnesium, and titanium. Various solution, precipitation, ion exchange, and electrolytic steps follow to separate the individual salts so that each one of them can then be reduced using sodium to their pure metallic form. The process can be adapted to deal with other potential lunar minerals or concentrates, including feldspars, pyroxenes, olivines, and even nonsilicates such as ilmenite and spinels. One advantage of this method is it does not demand prior beneficiation of the raw material, because the relevant separations are performed subsequently using the fluorides and fluorosilicates.

HF leaching has been shown to provide the best potential for minimum mass of the operating equipment, ease of element separations to high purity, and favorable energy and heat-rejection needs. On the other hand, it may be difficult to find a container that is suitable for the process because hydrofluoric acid is a potent substance which attacks vessels and tubing. One option might be special carbon steel

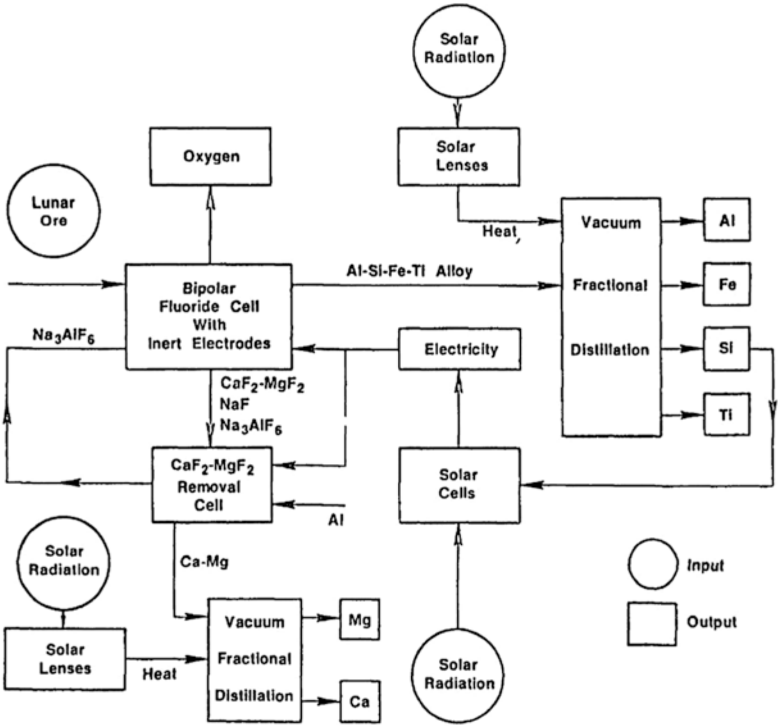

Figure 4.14 A proposed system for lunar extraction of oxygen and metals.

alloys already developed for storage of fluorine gas. They form a protective layer of iron fluoride which greatly impedes further chemical attack. Another option might be hydrocarbon-based waxes, paraffins, or plastics because these are not attached by HF. They could coat the interior surfaces of vessels and tubing. A third alternative would be to develop new structures using sulfur, phosphorus, and inorganic polymers that could probably be obtained from the lunar surface.

Resource Recovery from Asteroidal Material

Water recovery from an asteroid can be achieved by gently heating with a solar furnace the clay mineral present in carbonaceous chondrites. This would be just enough to raise the surface temperature to 200-300°C. Condensers then collect and store liquid water. Oxygen can be extracted by electrolysis. The hydrogen that is released can be used as propellant in conjunction with oxygen, or employed as a powerful chemical agent for materials processing. Oxygen could be derived from ilmenite but that process requires much more energy. The energy needed to extract 1 tonne of oxygen from 10 tonnes of ilmenite is ten times greater than that to get the same amount of oxygen from 5 tonnes of carbonaceous asteroid. Furthermore, an external source of hydrogen is required for extraction of oxygen from ilmenite.

Recovery of iron, cobalt, and platinum-group-metals can use the gaseous carbonyl (Mond) process. The CI meteorites have 6% organic matter, mainly in the form of an involatile polymer that is mostly carbon but also nitrogen, hydrogen and oxygen. These meteorites also have 40% magnetite, a magnetic mineral with formula Fe_3O_4. Using hydrogen (derived for instance from electrolysis of water) magnetite can be reduced to pure metallic iron with the water as a useful byproduct.

A fusion torch and vacuum fractional distillation would also work, although for the latter a certain degree of artificial gravity will have to be provided. Magma electrolysis of a silicate melt is another option, giving oxygen gas and a mixture of several elements such as iron, nickel, magnesium, silicon, calcium, and aluminum. Again, a fusion torch or vacuum fractional distillation or differential melting can provide further processing and separation of the individual elements.

The nitrogen in the organic matter of carbonaceous chondrites can be extracted by destroying the involatile polymer using oxidization. It will produce a mixture of carbon monoxide, nitrogen, water vapor, and a trace of sulfur oxide. By freezing the water, all of these gases can be dried out and hence treated with hot hydrogen gas (which might be derived from the electrolysis of water) to create a new mixture of methane, nitrogen, and more water (this fresh water comes from the reaction of hydrogen with the dried carbon monoxide). Once again, the water is frozen and the resulting nitrogen-methane mixture can be liquefied and later separated using distillation. Methane is an excellent propellant choice because it is storable, is easy to condense and transport, and is denser than hydrogen (and hence requires smaller tanks). On the other hand, it is less potent than hydrogen in terms of energy. And of course, nitrogen can be used for life-support, for farming, and as a fire suppressant.

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IMAGE LINKS

Figure 4.1: NASA SP-509 Space resources. Volume 3: Materials. (1992). [pdf] NASA, p172. Available at: http://www.ntrs.gov [Accessed 24 Jul. 2019].

Figure 4.2: NASA SP-428 Space Resources and Space Settlements. (1979). [pdf] NASA, p.289. Available at: http://www.ntrs.gov [Accessed 24 Jul. 2019].

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Figure 4.6: NASA SP-509 Space resources. Volume 3: Materials. (1992). [pdf] NASA, p227. Available at: http://www.ntrs.gov [Accessed 24 Jul. 2019].

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Figure 4.14: Extraterrestrial materials processing and construction. (1980). [pdf] NASA, p.250. Available at: http://www.ntrs.gov [Accessed 24 Jul. 2019].

5

The Art of Manufacturing in Space

MANUFACTURING IN SPACE: A PROLOGUE

We have outlined the resources the Solar System offers and how we might go about extracting and processing them.[1] Now we shall examine how such resources can be exploited to manufacture goods that will benefit humankind.

The concept of manufacturing products and infrastructures in space is almost as old as the Space Age itself. In fact, since the late 1960s, NASA and other institutions have been seeking ways to exploit the distinctive properties of the space environment for innovative manufacturing processes, such as drugs for pharmaceutical purposes, new materials with exotic properties, components for large space stations, and so on. The first experiments were performed in the mid-1970s on board Skylab, America's first space station. This work carried over to the Space Shuttle and is a fundamental part of the International Space Station. Similar experiments were also carried out on the Salyut and Mir stations of the Soviet/Russian program.

These experiments have prompted the scientific and engineering communities to develop ways of manufacturing in space. Their products include truly spherical ball bearings, high-purity crystals for pharmaceutical and metallurgical research, casting of complex objects, vaccines, long high-strength filaments for composite materials, and so on. These successes have been reported by popular science outlets as well as in the technical literature. Often, experiments seek to improve our understanding of phenomena that can be fully analyzed only in a laboratory where the influence of a gravity field is absent. Typically the intention is to unravel their behavior to improve existing numerical and analytical models in order to enhance

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[1] Our survey merely dipped into the immense technical literature that is available.

D. Sivolella, *Space Mining and Manufacturing*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-30881-0_5

the efficiency of a given fabrication process or product. For instance, considerable efforts have been devoted to investigating the process of combustion. This could make engines more efficient and less polluting. It could also result in materials that have superior fire retardant properties. There is no doubt that such theoretical studies can provide scientific and technological advances. They also provide a significant basis for the development of a space-based manufacturing capability. But what is often underrated and neglected is that space can enable us to work with processes and physical conditions which on Earth are either unattainable or are attainable only using expensive and sophisticated apparatus. For example, the manufacture of microchips requires using deep vacuum chambers and atmosphere-composition-controlled chambers. On Earth we live in an atmosphere with a composition and density that is well-suited to life, not industrial manufacturing, and therefore we need expensive and complex machinery to achieve the desired conditions.

The aim of this chapter is not to focus on which specific products can be made in space, nor on how the properties of space can improve the quality of goods currently serving applications here on Earth, nor indeed to examine those areas of fundamental research that improve our understand of phenomena which are of interest only to the narrowest of scientific circles.

Transferring our industrial efforts into space has the merit of sparing the Earth's environment from pollution caused by the extraction, generation, and transportation of matter and energy for the fabrication of goods, as well as their wastage during the manufacturing process itself. In space, where there is not a biosphere to preserve, the issues concerning environmental pollution no longer apply.

In this chapter, we will demonstrate that even if space offers an environment with unfamiliar attributes that do not occur naturally on Earth, it will still be possible to develop manufacturing capabilities comparable to those with which we are familiar.

Let us start by considering what the space environment has to offer, then define several industrial processes it will facilitate. We will conclude by speculating about a possible factory in space.

THE SPACE ENVIRONMENT

Sixty years of human spaceflight have accustomed us to objects that defy our daily experience of gravity. Astronauts on board the International Space Station fly like Superman, seemingly liberated from the force that keeps the rest of us bound to the floor. Objects in space are said to be in a state of 'weightlessness' or 'zero-g',[2] but

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[2] The amount of gravity we experience here on Earth is referred to as 'g'. At sea level it has an average value of 9.81 m/s^2. In rocketry accelerations are frequently expressed as multiples of 'g'. For instance, an acceleration of two-g corresponds to a value double that of g. At times, 'g' might be replaced by the annotation 'gee'.

this does not mean there is no gravity there. To understand why, think of yourself as a baseball pitcher and suppose you are on an airless field as vast as planet Earth, with no obstacles in your way.[3] The faster you throw the ball, the farther away it will fall from you and the greater the curvature of its trajectory. At a certain point, you might throw the ball so fast that its trajectory becomes a closed circle, never falling to the ground. The ball is in orbit! In effect, even though the ball wants to fall, the ground drops away from it at a rate equal to the curvature of the trajectory. Gravity is trying to pull the ball down to the ground but the ball is destined never to make contact. It is in an endless state of 'free fall'. A spacecraft is in the same situation. This explains why being in orbit around a celestial body is a matter of horizontal speed, rather than altitude. However, for a body such as Earth that possesses an atmosphere, to achieve orbit it is first necessary to achieve an altitude sufficient that the residual atmosphere does not impose so much drag as to cause the spacecraft to lose forward momentum, re-enter the denser atmosphere, and either burn up or strike the ground.[4]

The ascent trajectory of a rocket is designed to follow a sort of outward spiral, so that as it gains altitude it also achieves the minimum horizontal speed necessary for a stable orbit. This velocity depends on the mass of the celestial body, and in the case of Earth it is 7.8 km/s (about 28,000 km/h). For horizontal speeds greater than this, the orbit becomes an ellipse whose lowest point (called periapsis) corresponds to the altitude at which the engines were shut down and whose highest point (the apoapsis) is the height at which gravity halts the ascent and recalls the vehicle. To increase the apoapsis you must impart a greater velocity so that the vehicle has more momentum and travels farther before being recalled. So we see that gravity is *always* influencing the spacecraft in orbit. However, if the tangential velocity is sufficient, the spacecraft will have enough momentum to escape gravity and follow an 'open trajectory', either a parabola or a hyperbola depending on the energy, that will never fall back to the body from which it was launched. Nevertheless, even a spacecraft in 'deep space' is influenced by the gravity of the Sun. Only a few of our probes have been accelerated sufficiently to escape the Solar System.

Once in orbit, the objects inside the spacecraft travel at the same velocity as the vehicle itself. They, too, are in free fall. Since the interior of the spacecraft remains motionless with respect to its contents, it follows that we *perceive* the condition of weightlessness. But gravity is still operating.[5] In the spacecraft, if both the frame

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[3] This is what scientists refer to as a 'thought experiment'.

[4] When you throw an object, the distance to the impact point is affected by friction with the ambient air, which in turn is influenced by the shape of the object. In the absence of air, the impact point would be further away.

[5] Next time somebody says that there is no gravity in space, ask them to explain how the Moon, or for that matter an artificial satellite, can orbit Earth. If there were no gravity, surely the Moon would not feel compelled to endlessly circle our planet! However, because the force of gravitational attraction follows the inverse square law, its intensity decreases the farther away two bodies are from each other. A doubling of distance means a four-fold reduction in the intensity of the gravity field.

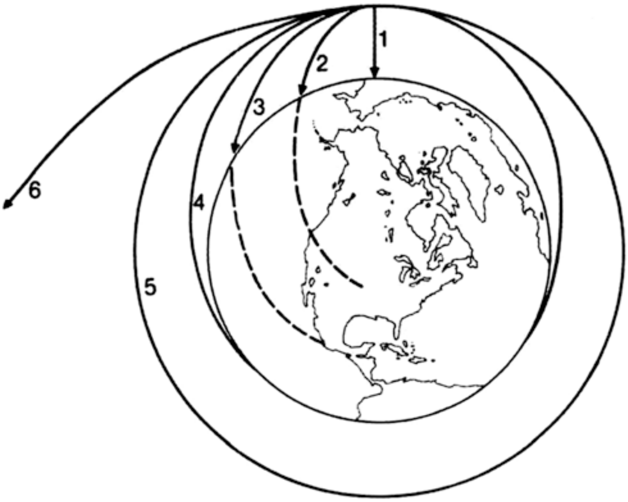

Figure 5.1 Orbital paths of falling bodies about Earth. If there is no tangential velocity, the body falls straight down (trajectory 1). As the tangential velocity is increased, the point of intersection with the ground moves farther away from the launch point until it enters a close orbit that never intercepts the ground (trajectories 2 to 5). Further increasing the tangential velocity confers sufficient momentum to escape into deep space, never to return.

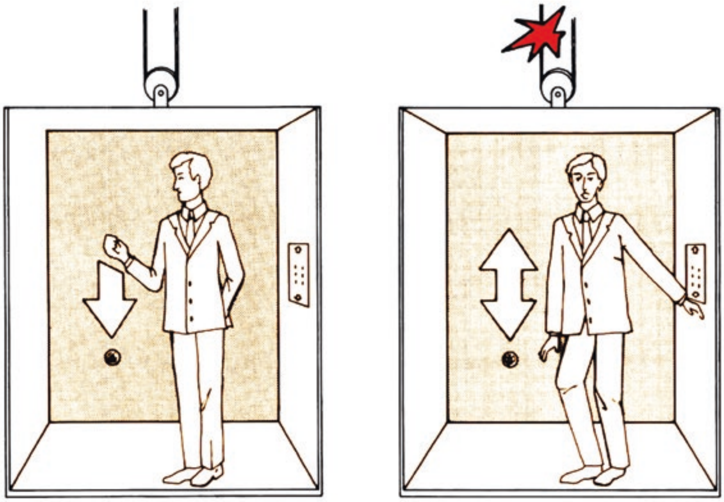

Figure 5.2 The Principle of Equivalence. On the left, a man on Earth's surface drops a coin. It falls to the floor with an acceleration of 9.81 m/s^2, that being the acceleration due to gravity at Earth's surface. On the right, the rope holding a lift is cut and it falls. Its contents will fall at the same rate. If the man in the falling lift drops a coin, it will behave in the same manner as before except that because it has no motion relative to the lift it will float in midair, as if in a state of weightlessness.

of reference and the objects inside it are traveling at the same velocity there will be no relative motion. The objects will *appear* not to be in a gravity field. This Principle of Equivalence was formulated by Albert Einstein as part of his Theory of Relativity. In simple terms, it says that the internal behavior of a system in free fall is equivalent to that of a system far removed from a gravity field.

A zero-g environment is an 'ideal' condition that can never truly be achieved in orbit because there exist a number of kinetic effects that create artificial gravity-like forces. Orbital mechanics states that the closer a vehicle is to Earth, the faster it will travel. In a spacecraft that maintains an inertial orientation,[6] any loose contents will slowly lead or lag behind the overall center of mass depending on whether they are closer to or farther away from Earth than the center of mass, respectively. Eventually, all loose objects will reach the walls as if drawn there by an external force. The same occurs if a spacecraft slowly rotates in order to maintain a fixed orientation relative to a specific point on Earth's surface. This will contribute an extra motion in addition to that of the inertial case. The acceleration is about 10^{-7} g (a ten-millionth of Earth's gravity) for every meter of displacement from the spacecraft's center of mass.

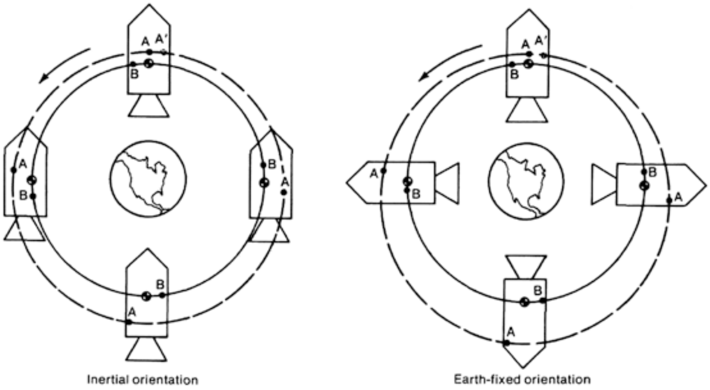

Figure 5.3 Motion of objects inside a spacecraft. Regardless of the orientation, any object that is not at the precise center of mass of the spacecraft will slowly follow a trajectory that comes into contact with a wall.

Another source of disturbance is the presence of the atmosphere. Although orbital space is a vacuum by human standards, there are sufficient atoms and molecules to impose a continuous drag on a spacecraft traveling at orbital velocity. As the vehicle decelerates, loose objects inside will experience a relative motion.

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[6] This is a condition in which the attitude of the spacecraft is held fixed with respect to a target such as a star.

Other extraneous accelerations arise when an astronaut moves around. The third law of motion states that for every action there is a corresponding opposite reaction. If an astronaut pushes against the wall of a spacecraft, that reacts with a movement in the opposite direction. These accelerations are tiny at 10^{-2} to 10^{-4} g, but they can disturb extremely sensitive experiments.[7]

Matter in a solid state is composed of atoms and molecules that are tightly packed against each other, held in position by chemical bonds whose strength is many orders of magnitude greater than that of gravity. Hence gravity does not affect the properties of solid state matter. Even when an object is subjected to an acceleration many times that of gravity, such as during a rocket launch or atmospheric re-entry, depending on its design and size, it may be torn apart but the behavior of the matter from which it is made will not change. This is in contrast to the behavior of matter that is in a fluid state.[8] Here the intrinsic properties of cohesion and surface tension are of the same order of magnitude as gravity. As a result, fluid state matter is profoundly influenced by gravity. In particular, this gives rise to phenomena such as buoyancy, hydrostatic pressure, and gravity-induced convection.[9]

When a particle is immersed in a fluid that is in a gravity field, it is subject to a buoyancy force defined by the product of its volume, the acceleration of gravity, and the difference in density between the particle and the fluid. This force produces an acceleration that makes the particle rise, settle, or sink depending on the sign of the difference in density.[10]

Hydrostatic pressure obliges a fluid to deform under its own weight, and triggers the mechanism of gravity-induced convection. Convection is the result of differences in density brought about by differential heating within a fluid. Consider when water boils. The water at the bottom of the pot is warmer and starts to expand. This makes it less dense and therefore lighter. The colder column of water above, being denser and therefore heavier, is driven by gravity to displace the lighter water. On reaching the bottom of the pot, it too can be warmed up. Once away from the heat source, the warmer water cools, becomes denser, and sinks. This cycle of water moving up and down inside the pot will be maintained until either the source of heat is removed or all of the liquid has evaporated from the exposed upper surface.

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[7] Such values for g depend on the inertia of the spacecraft and on how hard the astronaut pushes off and stops.

[8] It is worth recalling that a fluid corresponds to either a liquid or a gas.

[9] We specify gravity-induced convection here because there are other sources of convective motion, such as variable surface tension and non-uniform thermal expansion.

[10] If a particle's density exceeds that of a fluid it will sink; if it is the same it will settle in the position where it was first placed; if it is lower it will rise. Hence a rock sinks in water, a boat floats on the surface, and a submarine can remain safely underwater.

The internal motion caused by gravity-driven convection is of concern in the process of solidification for two reasons. Firstly, motion enhances nucleation and is therefore undesirable in all processes that require control of crystallization. Secondly, convective currents may induce imperfections during crystal growth, such as dislocations, that will impair the properties of the end product.[11]

Buoyancy, gravity-induced convection, and hydrostatic pressure all cease to exist in the weightlessness of orbital flight.[12] Liquids become objects in their own right, subject only to surface tension. Density is no longer the dominant characteristics of a material. They will adopt the shape that minimizes surface tension energy, namely that of a sphere. Phenomena which are usually masked by gravity become manifest, particularly the Marangoni effect. Named after Carlo Marangoni, the Italian scientist who studied it for his doctoral dissertation at the University of Padua in 1865, this is a convective motion triggered by a gradient in surface tension. Such a gradient might result from a difference in chemical composition or temperature between two points in the fluid and it will set in motion the transfer of liquid towards the region of higher surface tension because that pulls more strongly on the surrounding fluid. Industrial processes on Earth can sometimes utilize this effect. For example, it is used in drying silicon wafers after a wet processing step in the manufacturing of microchips. In this case, after the wafer of silicon is lifted out of a bath, not all the liquid flows back into the container, some remains attached to the wafer and forms meniscuses. Air mixed with an organic compound is blown over the wet surface with the aim of increasing the surface tension of the meniscuses so that they can draw more water towards them and form droplets of liquid. On becoming too heavy, the droplets fall off, leaving a dry surface. In zero-g, the Marangoni effect is much more effective.

A ramification of lack of buoyancy is the absence of sedimentation. On Earth, as particles approach micrometer sizes, their gravitational potential energy matches the thermal energy of the molecules in the liquid. This means that the random molecular collisions create forces comparable to the buoyant forces and the particles tend to be held in suspension by these random velocities.[13] Hence in Earth's gravity it is possible to maintain a stable suspension of particles only if they are smaller than approximately one micron in size. In a low-gravity environment it should be possible to maintain a suspension of much larger particles. This can be both an advantage and a disadvantage. For example, it should be possible to investigate processes involving suspensions such as chemical fining

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[11] Nucleation is the first step in the formation of either a new thermodynamic phase or a new structure via self-assembly or self-organization. Dislocations are an irregularity within a crystal structure and their presence strongly influences many of the properties of materials.

[12] For the remainder of the book, we will use the terms weightlessness and zero-g in an interchangeable manner and take for granted that in the free-fall environment of orbital flight they are only apparent conditions, as defined by the principle of equivalence.

[13] This is known as Brownian motion.

of glasses, preparation of unique foams, polymerization processes, and preparation of immiscible alloys. On the other hand, many convenient separations provided by buoyancy which we tend to take for granted on Earth, such as the removal of unwanted bubbles, will not occur. In a low-gravity environment, attention must be given to alternative techniques for accomplishing these important separations.

At sea level the composition of Earth's atmosphere is 21% oxygen, 78% nitrogen, and traces of other elements. At an altitude of 400 km, where spacecraft in low orbit travel, the atmospheric density is less than one-billionth of that at the surface and the pressure is approximately 10^{-7} torr. It is a mixture of atoms of oxygen, nitrogen, and helium whose precise composition varies with the state of activity on the Sun.[14] As a consequence of the low density, heat transport can only be accomplished by way of radiation balance. The equilibrium temperature of a spacecraft is that at which the heat lost in the form of infrared radiation is equal to the sum of that absorbed from the Sun, the radiant energy absorbed from Earth, and the heat it generates itself. The near vacuum also makes non-metallic materials such as paint, binders and adhesives outgas considerable amounts of vapor which, on leaving their place of origin, quickly settle elsewhere on the vehicle's skin. By reacting with the ultraviolet component of unfiltered sunlight, a coating formed from these vapors can interfere with the optical and thermal control performance of a variety of components.[15]

The space environment also offers the full spectrum of electromagnetic radiation from the Sun. And there is the solar wind, composed of electrically charged particles that are capable of ionizing a variety of materials. Plus there are extreme differences in temperature. For example, the permanently shadowed floors of craters in the polar regions of the Moon have been measured at 35 K. The corona of the Sun is millions of degrees. In space, solar energy is freely available. It can be channeled, for example by mirrors, to produce the intense heat required for an industrial process.

MANUFACTURING IN SPACE

Containerless Processing

Owing to the ever pervasive one-g environment on Earth, any industrial process has either to happen within a container or be held in place, manipulated, and transported using sophisticated apparatus which is designed to counteract the pull

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[14] Conditions on the Sun influence Earth by way of the solar-terrestrial relationship.

[15] Apparatus for astronomical or planetary observations are protected with covers that are released only after sufficient time has elapsed to allow the outgassing to take place and thereby avoid contamination.

of gravity. The presence of a container introduces a number of wall effects such as nucleation sites, contamination, and induced strain. On Earth, semi-containerless methods have been developed to minimize such effects in the manufacturing of materials that require an increased level of purity or precision, such as silicon wafers for microchips.

One process is the so-called Czochralski method, in which a seed of pure silicon is lowered into the free surface of a high-purity silicon melt that is inside a crucible.[16] As the seed is slowly pulled away from the melt, the molten silicon adheres to it and solidifies to produce a single large cylindrical crystal that can later be sliced into thin wafers. This process was introduced in 1917 and offers the advantage of producing a product free of the physical constraints imposed by the container. But the container can still introduce contaminants into the melt. For an application that is as sensitive to impurities as the production of microchip wafers it is necessary to use a crucible made of materials that will minimize impurities. Quartz is widely used, even though the small amount of oxygen that it releases will pollute the silicon. Contamination is further reduced by executing the process in an inert atmosphere that prevents it from reacting with the melt. Ideally, the crucible is isolated from external vibrations which would impair the growth of the crystal.

An alternative is the floating zone method. This consists of holding a rod of solid silicon and moving a heating element, such as an induction coil, from one end to the other. The heated area melts but does not drop off because it is held in place by the surface tension of the liquid. As the heating element travels to the other end, so does the molten zone. Impurities have a segregation coefficient of less than unity, so they do not easily integrate into the molten material. Contaminants are pushed in the same direction as the molten zone and collect at the end of the rod. As the heating element never touches the material of the rod, the floating zone process offers a better purity than the Czochralski method. However, the process is strongly influenced by gravity, which limits the size of the molten zone. As a result, this process can be applied only for materials whose surface tension can contain the liquid phase against hydrostatic pressure.

A third option to avoid container-induced contamination is called skull melting. It consists of heating the interior of the crucible while refrigerating the outside by pumping coolant through coils that surround it. In this way, a solid layer of the melt material is formed on the container's internal wall and the molten material interacts only with its own solid, and not the crucible. The disadvantage is the lack of control in the process of solidification. What is more, there will be thermal gradients and an uncontrolled convective flow at the solid-liquid interface. Control of nucleation and growth of the solidification is therefore virtually non-existent.

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[16] The melt is also doped with trace amounts of elements such as boron or phosphorus to produce wafers with specific electric properties.

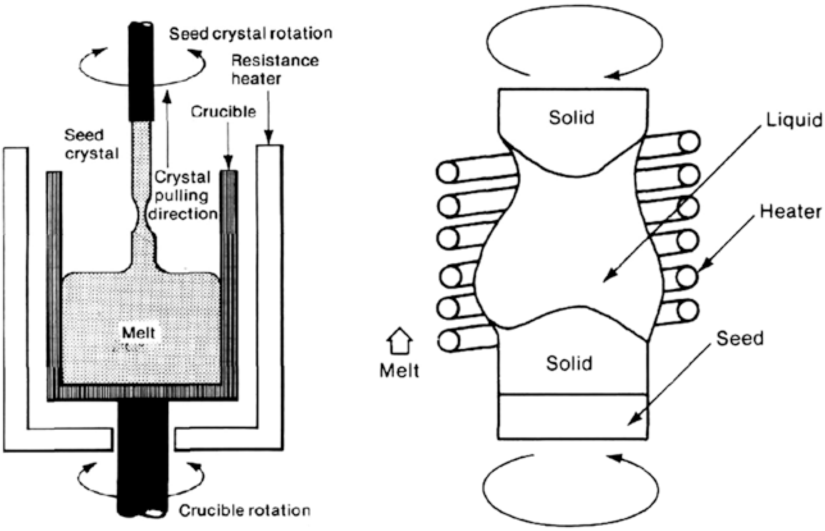

Figure 5.4 The Czochralski method (left) versus floating zone (right).

These are only a few examples of how terrestrial manufacturing processes have to contend with gravity and the nuisances introduced by the presence of a container. Of course, not every product requires as high a purity as making a silicon wafer, but vessels are still needed, as are tools for manipulating and controlling the process.

A state of weightlessness offers considerable simplification, because it facilitates containerless processing such as melting and solidification, and requires a negligible tool interface to perform movements. On Earth, metallurgists have been conducting levitation melting for many years using electromagnetic force fields to create small globules of metals that are solidified without the possible contamination of a crucible or vessel. But this method is impractical outside the realm of experimentation, since it takes a great deal of energy to counteract the pull of gravity of even a small amount of material. Furthermore, such energies induce electric currents and violent stirrings that aid melting but severely limit solidification. In a state of weightlessness this will not occur because considerably less force is needed for handling and positioning. In weightlessness, everything is in free fall relative to its surroundings, and thus can be said to be levitating. There is no need to spend energy to create a levitating condition, it is provided for free. All that is needed is to move the material to be processed from one workstation to another. It takes very little effort to overcome the marginal forces that are imposed on objects in free fall inside a spacecraft due to the effects of orbital mechanics and the small residual accelerations which influence a vehicle. In fact, the forces required to hold a material specimen in position inside a processing apparatus are of the order of 10^{-4} to 10^{-6} of the terrestrial specimen's weight. Several options exist.

If a material possesses some conductance then coils can apply electromagnetic, electrostatic and magnetostatic fields for positioning. For good conductors, position control uses interaction between the applied alternating fields and the eddy currents induced in the processed specimen. This would work both under vacuum conditions and within an atmosphere. In a gaseous environment, acoustic drivers similar to loud speakers could exert an acoustic radiation pressure. In either case, by an appropriate spatial arrangement of coils or acoustic drivers and the use of frequency modulation it is possible to achieve 3-axis translational and rotational control. Use of rotational control could easily facilitate materials of high purity without requiring a container. For instance, a sphere of liquid can be made to spin. As it spins ever faster, it flattens into an ellipsoid and then a torus. By this time any dissolved gas or lighter materials will have separated. If the spinning is halted, the purified liquid will resume a sphere. Mechanical positioning using robotic arms or the like might be advantageous, such as retrieving an object from a processing chamber after it has cooled. Eddy current intensity sensors, heat detectors, and electrostatic capacitors would be used for position or handling control of free-floating materials, either liquid or solid. Another possibility is optical sensing, for example by detecting the radiation emitted by a hot object or by how it intercepts light beams, or perhaps by photography. It is quite likely that none of the above methods will apply to *all* processes, but that each one will have its nominal domain and that multiple techniques will be used at the same time.

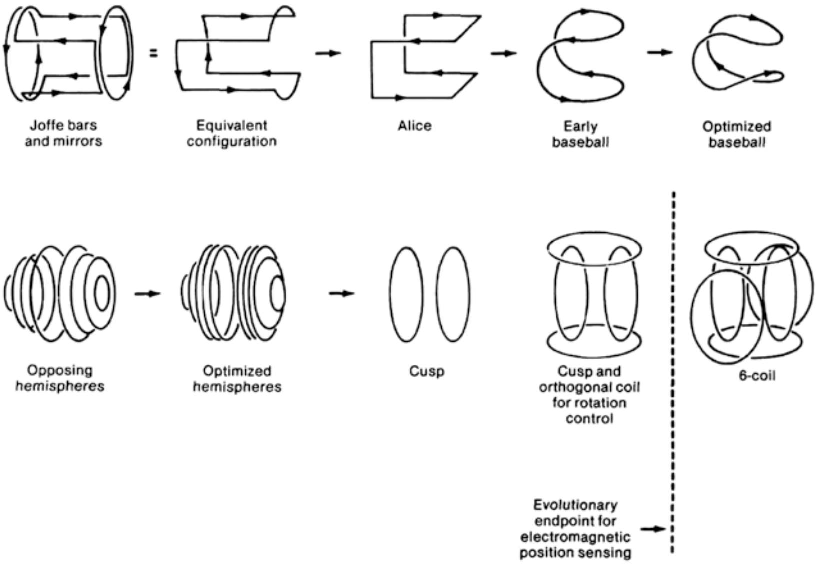

Figure 5.5 A coil configuration to provide basic 3-axis positioning for a low-gravity electromagnetic contairnless processing facility.

Generally speaking, freely floating melts are to be expected to oscillate in shape, so the magnitude of applied positioning accelerations has to be tailored according to the mass and material in order to prevent rupture of the floating mass. For materials of reasonably high melting points the upper limit to the mass that can be processed in a space facility will probably be determined by the available heating power source. For low melting points, surface tension for the maintenance of mass integrity may become the upper limit on workable mass size.

The electromagnetic fields utilized for position control and transport of specimens can also serve as a highly controllable heat source with which to perform zero-gravity melting. Absent the restrictions imposed by the material of a container, a specimen can be heated to a temperature well above its melting point. Superheating offers the ability to liquefy almost any material. Any impurity in the specimen can be destroyed, so that during cooling and solidification, nucleation sites that destroy the crystalline structure are avoided. And the subsequent cooling can occur at the very high rates afforded by radiation. This permits undercooling solidification, a condition where even if the liquid is at a temperature below that of solidification, the phase change to the solid state does not occur. This is difficult to achieve and maintain in a terrestrial setting because of boundary layer effects between the liquid and the wall of its container and nucleation that results from thermal eddies in the liquid when it undergoes a thermal change. In zero-g, these complications cannot arise. With supercooling, much of the shrinkage occurs in the liquid state, meaning that less stress is imposed upon the material during solidification. Closing a mold on a highly supercooled liquid prompts instantaneous solidification and the product is free of the induced stresses that typically impair the process in a gravity field. Other benefits of supercooling are mono-crystalline objects of considerable size and remarkably finely grained metals which are very stretchable (superplastic).

Containerless processing in the weightless state of space affords several attractive manufacturing processes such as cohesion casting, where the molten material is spun to create perfect bodies of revolution. It is also possible to use electrostatic fields to nudge the material into irregular but repetitive shapes.

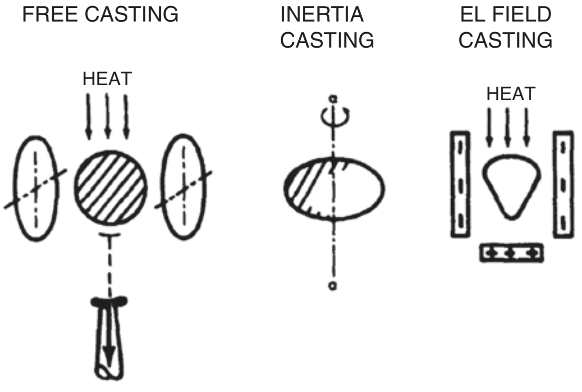

Figure 5.6 Principles of cohesion casting.

Adhesion casting is another option. It is based on the capillary forces which allow a liquid to spread across a surface. Under zero-g, relatively thick and uniform layers of material can be build up on the interior or exterior of a mold or form, and remain in place owing to the adhesive forces. It is also possible to float layers of metals and non-metals inside or outside a mold in order to produce parts. Adhesive and cohesive forces allow a liquid to be formed into thin wires, tubes, and membranes without risk of contamination.

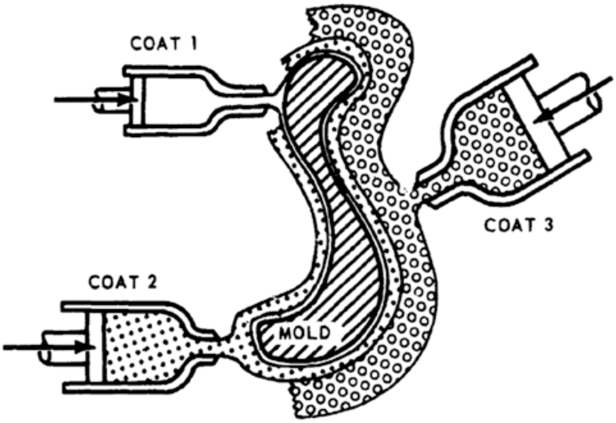

Figure 5.7 Principles of adhesion casting.

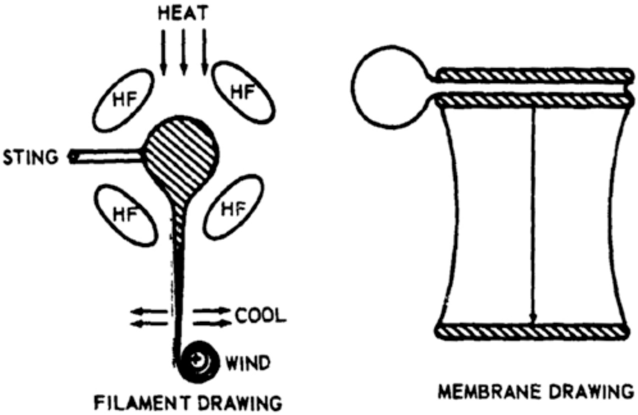

Figure 5.8 Principles of surface tension drawing.

Containerless processing, in combination with the absence of buoyancy, gravity-driven convection and hydrostatic pressure also permits the mixing of liquids which cannot be put together on Earth because of differences in density and surface tension. In the density-insensitive environment of space, materials can be combined without separation. The mixing process is more uniform and homogeneous and occurs at lower temperatures. Alloys are created at high temperature because most metals can mix only above their melting points. Low-temperature alloying reduces the energy required for the process. The formation of in-situ composites from immiscible systems may also be attainable. Some 500 alloy systems have a ‘miscibility gap’, which means that there is a region in the phase diagram where the two molten materials will not mix (rather as oil and water will not mix). Alloys of such systems cannot be formed by conventional solidification because the melt must be cooled through this miscibility region in order to solidify. As a result of having different densities, the two liquids immediately come out of solution in normal gravity. If such composites can be made in space, this would make possible a search for new systems that have interesting mechanical and electrical properties; for example, high transition temperature superconductors that can be easily drawn into wires, unique bearing materials, improved electrical contact materials, and alloys with high strength-to-weight ratios.

Furthermore, a density-insensitive environment offers the option of working with bubbles. For a soap bubble under the influence of gravity the liquid that surrounds the air is drawn from between the outer and inner surface tension layers. When they touch, the bubble bursts. In zero-g, stability is achieved because the liquid cannot drain. Thus sizable bubbles can be blown, even with a metallic material. In fact, it may be feasible to blow large, thin-walled bubbles to produce membranes of metals, glass, or other inorganics.

Because bubbles do not rise to the surface in zero-g but remain mixed within the ambient material, we have the possibility of controlling their distribution and size to create so-called foamed materials with customized physical properties. For instance, it may be possible to create a material with the same low density of balsa wood and the high-temperature and high-strength properties of steel. Ductility can be increased because the stress generated by bending is redistributed through the bubbles. Another possibility is to lower the density to less than that of water. Materials that float would benefit deep sea applications. The dispersion of the perfectly spherical gas inclusions can be so fine as to maintain a high equilibrium pressure. Such materials are difficult to produce on Earth because gravity, convection, and density differences play against the stabilization of the foam, prompting the bubbles to rise to the surface and burst. A remedy is to rapidly cool the material to prevent the bubbles from rising, but it is still difficult to create foams with uniform and repeatable characteristics in a one-g environment. In zero-g, where differences in density to do not matter, the distribution of bubbles is more readily controlled. The material can be cooled gradually to ensure repeatability in the quality and properties of the product. We can use any mixture of metal and gases, because the air surrounding the manufacture of foam metals can be controlled to suit the product.

Ultrahigh Vacuum Processing

Thus far, we have focused on processes that capitalize on zero-g and the absence of gravity-driven phenomena. But manufacturing in space is not just about exploiting the state of weightlessness. Space offers other useful properties. There is an ultrahigh vacuum beyond any reproducible on Earth. Nevertheless, a spacecraft can be likened to a ship producing a bow wave and a wake as it makes its way across the sea surface. In traveling at a speed of 7.8 km/s (about 28,000 km/h), a spacecraft will push aside any atoms in its path and produce a bow wave with a pressure of 10^{-4} to 10^{-6} torr, depending on altitude and orientation. It will leave in its wake a region of enhanced vacuum at 10^{-14} torr, a mere one-quadrillionth that at sea level.

This wake can be exploited by industrial processes that require a 'hard vacuum', particularly the manufacturing of silicon wafers for microchips and micro-electro-mechanical systems (MEMS). These devices feature structures in the micron, almost nanometer size,[17] and require sophisticated techniques to deposit materials on a silicon substrate (wafer) to build an exquisitely precise piece of hardware such as a computer chip or the accelerometer and gyroscope that enable you to play video games on your smartphone.

One such method is molecular beam epitaxy (MBE), also known as epitaxial thin film growth. Generally speaking, MBE is a powerful tool to synthesize new materials with prescribed characteristics and fabricate novel microelectronics devices. In simple terms, it shines one or more beams of atoms or molecules such as arsenic and gallium onto a prepared pre-heated substrate which forms an atomic template, or pattern, upon which the atoms or molecules are deposited to produce a thin film or layer that follows the existing crystal pattern. Multiple layers can be grown by a single process, all with a perfect interface to the surrounding strata. This is such a delicate process that it can only work under ultra-vacuum conditions in which the presence of contaminants that can spoil the film is almost negligible. There are limits to the level of vacuum that can be attained by Earth-based facilities because the deeper the vacuum that is desired, the more difficult and more expensive it becomes to achieve and maintain.

It is a straightforward task to 'harden' the already excellent vacuum of the space environment because its capacity for vacuum is infinite and perpetual. There is no need for large pumping power-hungry systems for its retention. A notable demonstration of this potential was undertaken in the 1990s with the Space Shuttle flying an apparatus called the Wake Shield Facility (WSF). It consisted of a 4-meter-diameter free-flying disk made of welded stainless steel. It was outfitted to function as a spacecraft on its own. On being released by the Shuttle's robotic

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[17] A micron is one millionth of a meter and a nanometer is a billionth of a meter.

arm, the WSF orientated itself with its disk perpendicular to the direction of travel to create an ultra-vacuum in its wake. In the center of the wake-side was a cylindrical canister called the carousel that could rotate about the axis parallel to the plane of the disk. It held seven gallium arsenide substrates, each of which had its own heater. Although silicon is the most widely used semiconductor for microelectronics,[18] there are also other materials of higher predicted performances in terms of power consumption and working speed. Gallium arsenide is one of those high-performance materials.

Only one substrate at a time was exposed to the vacuum in order to undergo the MBE process. Each thin-film-growth run started by rotating the carousel to expose the desired substrate to space. In that position, the substrate was directly facing the source cell assembly. This was the heart of the MBE apparatus, and consisted of a cluster of eight canted molecular beam source cells that were held in position by a structure with eight struts that aligned the center line of the assembly with the center of the sample in the carousel. In processing, heating from one of the source cells generated a molecular beam flux that deposited on the exposed substrate, growing a thin film, layer by layer. The carousel and cell assembly enabled experiments using different combinations of substrate and cell materials. For instance, cells containing gallium, arsenic, silicon, and triethylgallium were used to grow gallium arsenide and silicon-doped gallium arsenide membranes. Flux levels and growth rates were controlled using data output by a mass spectrometer and total pressure gauges. A high-energy electron diffraction system was used to monitor the quality and uniformity of the films.

The WSF flew on three Space Shuttle missions and successfully demonstrated that microchip manufacturing in space was feasible. It was seen as the first step on the road to industrial and commercial applications in space. The plan called for four test flights at yearly intervals in order to validate space-based thin film growth and commercially significant volumes of product. It was hoped that following a successful test program, industry would fully exploit this technology. The plan was to fly an upgraded WSF-2 by 1995 to process a greater number of, and wider range of types of thin films. It was to be commanded by a dedicated commercial payload facility on Earth. The following year, WSF-3 was to have an even greater production capacity by sporting solar panels, additional central processing power, and even a robotic substrate sample manipulation system for extended orbital operations. Finally, in 1997, WSF-4 was expected to grow up to 300 thin-film wafers, which was considered to be representative of a production batch for a significant and profitable industrial operation that would open the gates for the much sought commercial phase

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[18] A semiconductor is a material that behaves either as a conductor or as an electrical insulator upon careful manipulation and exploitation of its atomic properties.

called Mark-II. In this case, the free-flyer platform would be periodically visited by a Shuttle to retrieve a finished production run of about 300 wafers and replenish the raw materials for the next batch. Of course, there would be several platforms in orbit. Perhaps a single Shuttle mission would be able to service all of them on a single flight. It was expected that each Mark-II platform would have a 5-year operating life.

Sadly, none of this became a reality. If NASA, and the industry in general, had had the necessary strategic vision we would, by now, be exploiting the space environment to produce at least one kind of commercially significant product that is difficult, if not actually impossible to produce at such high quality on Earth.

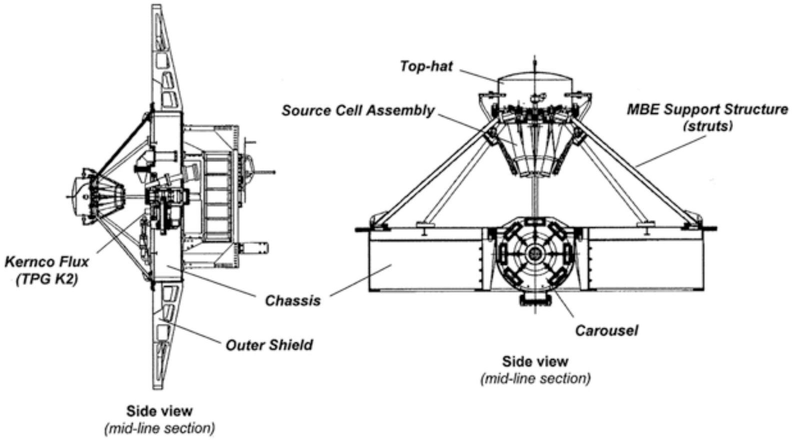

Figure 5.9 The main components of the Wake Shield Facility free-flying platform.

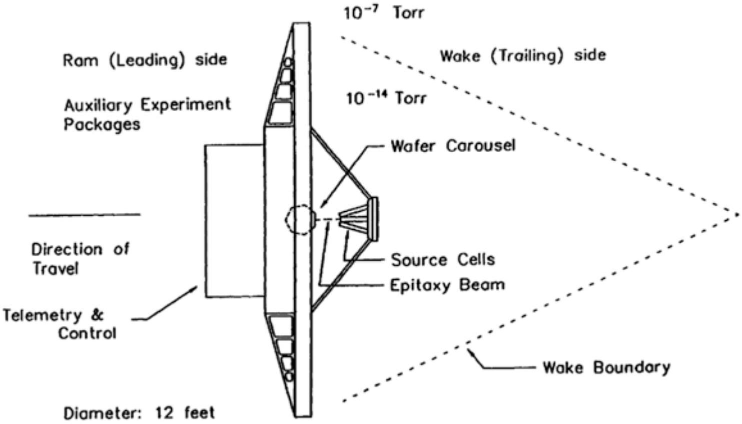

Figure 5.10 A demonstration of the MBE concept tested by the WSF.

Figure 5.11 The Wake Shield Facility is removed from the Space Shuttle's cargo bay. The source cell apparatus is visible on the wake side of the platform.

Space vacuum facilities such as the WSF offer the additional advantage of being able to apply higher heat loads than their terrestrial counterparts that use cryogenics to achieve and maintain vacuum. A space vacuum facility has a virtually infinite pumping capability. It would be ideal for preparing ultraclean surfaces, or for making ultrapure materials using high-temperature evaporation. The exciting prospects of containerless melting and solidification, and exploiting the vacuum in the wake of a spacecraft, are only now beginning to be considered. At an altitude of 500 km there is a better vacuum than can possibly be attained on Earth. Indeed, on Earth the harder the vacuum desired, the greater the sophistication and cost of the equipment. In space, which is a domain that has very little of anything, it will be possible to introduce conditions to satisfy the specifications of a given process.

Additive Manufacturing

Additive manufacturing (widely known as 3D printing) is a collection of production processes that are well-suited to the space environment, as shown by experiments on the International Space Station. In general terms, additive manufacturing is a process of building up a 3-dimensional object, layer by layer, until it is complete, rather than cutting a material in traditional subtractive manufacturing processes such as drilling and milling. This can be achieved in several ways.

Stereolithography (SLA) shines a laser beam on a pool of photopolymer resin,[19] both to outline the cross-section of the model for that particular layer and to cure it. Then the platform is adjusted by the thickness of a single layer and the next layer is added. This layer by layer process continues until the object has been built. A variant is Selective Laser Sintering (SLS) which utilizes a high-powered laser to fuse small particles of material and produce each layer. Compared to SLA, an SLS-built object does not need support during assembly because the unsintered material provides the necessary support. With Fused Deposition Modeling (FDM) the material is squirted from a nozzle that traces the cross-section pattern for successive layers.

Additive manufacturing offers several advantages. It can accommodate a diverse range of raw materials including glass, metal, ceramics, biomaterials, and plastics; it produces less waste because raw material can be reused; it allows manufacturing of complex components with fewer parts and an optimal shape that reduces the amount of unnecessary material, total mass, and cost; and it expedites production time. It has been eagerly embraced by a broad range of industries, including medical, aerospace, automotive, and consumer applications. The manufacturers of hardware for space, such as Boeing, SpaceX and Blue Origin, are already using this technology to reduce the number of parts in their rocket engines and to create structural elements.[20] And NASA is actively pursuing 3D printing in orbit because this offers a number of major benefits. The structural mass of an element of hardware can be reduced because the design is optimized for the microgravity loads that it will face in service, rather than the much higher loads of ground handling and launch. In addition, large structures made in orbit require fewer hinges, latches, and other complex mechanisms because they are built ready for use, rather than tightly folded for carriage. And incremental system upgrades are possible.

Founded in 2010, Made in Space, Inc., is at the forefront of developing additive manufacturing technology for use in zero-g. After 4 years and some 30,000 hours of development and testing of 3D printing, the technology demonstrator for use in space was sent to the International Space Station. It was so successful that in March 2016 it was joined by the Additive Manufacturing Facility (AMF), a permanent 3D printer which can construct complex objects to exquisite precision using multiple aerospace-grade materials. What is more, it can also work in a vacuum. In the meantime, Made In Space is continuing to test 3D printing capabilities for orbital space. For instance, by means of parabolic flights that simulate zero-g for periods of up to 30 seconds, it has been able to successfully print

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[19] This is a type of resin that changes its properties when exposed to light.

[20] Given the rapid progress in this field, rather than listing examples of additive manufacturing that have been implemented by these companies, and risk providing an out-of-date review, I suggest you make your own internet search to discover how the aerospace industry is exploiting 3D printing.

electronics, cast metal, and do 3D printing using stereolithography. It has even achieved bioprinting! For instance, using a proprietary method called Forced Metal Deposition (FMD) it was able to cast molten metal into a 3D printed mold to form a metal object. As stated by the company's website, "The introduction of this cornerstone terrestrial manufacturing technology to space allows parts to be produced in space in a well-known fashion, accelerating the adoption of this technology." Furthermore, "It also unlocks the potential for making entirely new kinds of metal alloys and structural designs that are not possible on Earth." It also prototyped methodologies to control the liquid layer and maintain it at the printing surface, not float off. "This demonstration was successful, producing accurate, high-quality parts in microgravity [and] this technology … will ultimately broaden our ability to respond to the unforeseeable demands of on-orbit manufacturing."

Another apparatus that is under appraisal is the Satellite Manufacturing Machine (SMM), a multi-material 3D printer and robotic assembly system. Using the SMM, Made In Space has built a small satellite that has the same functionality as Sputnik. Structure and circuit board substrates were additively printed, while a robotic device deposited electrically conductive traces and created electronic components such as a solar cells, integrated circuits, and a transmitter. The objective is a fully functional device to enable astronauts to fabricate multi-metal electronics. This would lead to in-situ repair or replacement not only of mechanical and structural elements but also of electronic devices such as sensors, printed boards, and other circuits.

As we shall see in the following chapter, manufacturing in space will be carried out in orbiting factories sporting components such as trusses, radiators, solar panels, modules, and so on. Generally speaking, space hardware is designed to survive the one-g environment in which it is built and the accelerations and vibrations of launch. Moreover, the size and shape of the aerodynamic fairing of a rocket impose stringent constraints on the mass and size of what can be carried. If the goal is to assemble a large structure in orbit, such as a space station or a radio telescope, multiple launches will be required. This complicates the design and increases costs and assembly time. The International Space Station was the first large structure to be assembled in this fashion. It is also likely to be a once-in-a-lifetime project, never to be repeated. The orbiting infrastructures of the future will hopefully be built in space by 3D printing systems that are fed raw materials mined from the Moon and asteroids.

But much research and testing will be required before this can become a reality. Made In Space is actively pouring time and resources into this type of operation. At the time of writing in 2019 they are creating Archinaut, a versatile in-space precision manufacturing and assembly platform capable of creating extremely large structures by combining space-proven robotic manipulation with additive manufacturing. The company intends to use Archinaut for in-space production and assembly of backbone structures for large telescopes, for automatic assembly of new space stations, and for repairing, augmenting, or repurposing existing spacecraft. It will be awhile before a goal as lofty as this can become a reality but the company is making good progress. In particular, in 2017 a prototype successfully manufactured multiple truss structures in a thermal vacuum chamber at the NASA Ames Research Center.

Made In Space is not alone in the quest to operate 3D printing in space. The same goal is also pursued by Tethers Unlimited, Inc., a space engineering firm founded in 1994 with the aim of building a robust in-space economy to serve the people of Earth and enable humanity to become a spacefaring society. Naturally, 3D printing fits the bill. One of the projects being developed is SpiderFab, a robotic system designed to extrude and pultrude high-performance structural elements and make them into large 3-dimensional sparse structures, rather like how a spider spins a web.

A typical SpiderFab robot is expected to have multiple highly dexterous robotic arms, both for mobility on the structure that is being built and for precise positioning of structural elements as the assembly takes place. On completing the structure, or a part of it, the robot can assist in the installation of reflective membranes, solar cells, sensors, payloads, avionics, cabling, etc. The typical joining methods would include thermal bonding, adhesives, and mechanical fasteners. The initial SpiderFab will use thermoplastic and high-performance fiber materials such as polyether ether ketone (PEEK)[21] and carbon fiber composites, but will eventually use a broader variety of materials including metals such as will be mined from the Moon and asteroids.

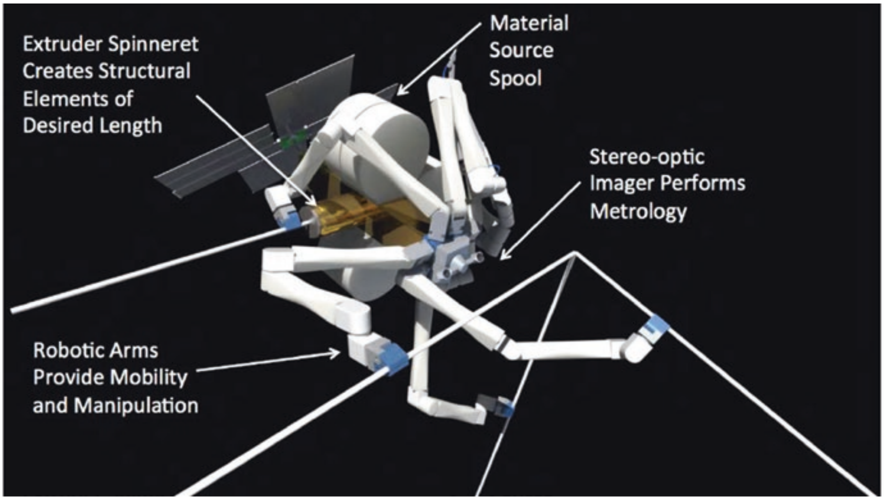

Figure 5.12 An artist's depiction of the Tethers Unlimited proposal for a SpiderFab robot that will 3D-print large structures in space.

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[21] Polyether ether ketone (PEEK) is an organic polymer in the polyaryl ether ketone (PAEK) family, the latter being an important class of commercial materials known as engineering thermoplastics.

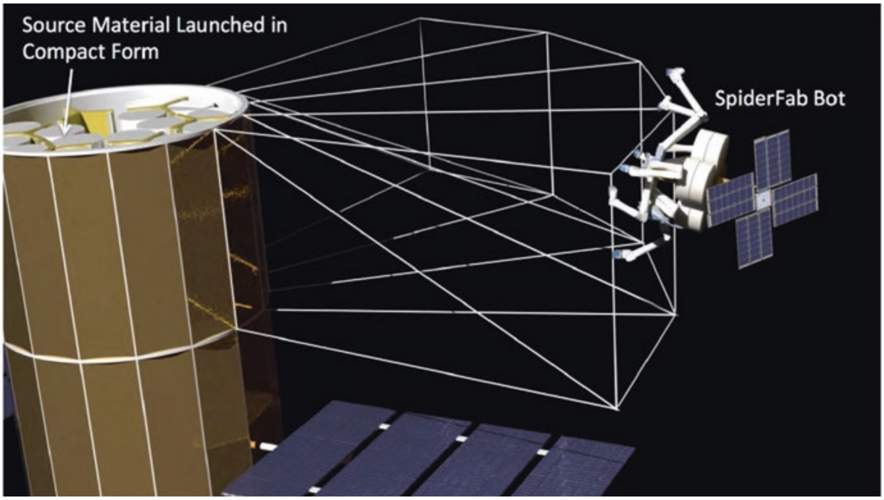

Figure 5.13 A SpiderFab Bot is building a support structure onto a satellite. Once complete, the system uses its robotic manipulators to traverse the structure and apply functional elements to the support structure, such as reflectors, membranes, meshes, or other functional components.

Processing is the Key

We could fill thousands of pages on how products could be manufactured in space. The technical literature is replete with papers detailing a great variety of processing methods that exploit the environment of space.[22] But it is not the purpose of this chapter to comprehensively review the literature. By now the message of this chapter ought to have be clear: the whole ball game in space is *process*! As mentioned at the top of the chapter, we all too often associate manufacturing in space with specific products, the use of which is often restricted to specific applications. This creates the impression that manufacturing in space can only be applied to niche products, rather than serve a wider manufacturing community. As a matter of fact, there is so much more than what meets the eye.

Environments which on Earth have to be created artificially to perform a variety of industrial processes, often at the cost of significant expenditures in terms of complexity and energy, are available for free in space. In addition to being able to carry out these familiar tasks more efficiently in space, the natural hard vacuum and incredible range of temperatures in space and the peculiar behavior of matter

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[22] If you want to know more on this topic, there are references at the end of this chapter. Another good starting point is the NASA Technical Report Server website. Just search for keywords such as "space manufacturing" and "processing in space". The results will keep you busy for hours.

and physical phenomena in weightlessness is an opportunity to develop brand new processes and methods that are not possible on Earth at all. It is simply a matter of taking advantage of the various phenomena of that environment in a way that accomplishes what we want.

For instance, plenty of industrial processes require high energy densities (very high concentrations of energy) to be applied and dumped for melting, smelting, vaporizing, solidifying, freezing, subliming, and fractionating. Space is mostly a low-energy place but stars are nodes of high-energy density and they can be exploited to operate with a wide variety of possible energy density gradients, far better than what can be done on Earth. Solar furnaces can concentrate and modulate that raw energy to suit a specific process. A wide range of temperatures can be achieved by using shields and radiators. The average temperature of interstellar space is just a few degrees above absolute zero. An object that is shaded from the Sun will soon plummet to cryogenic temperatures. If an application requires it, there are techniques for getting very close to absolute zero. Shields and radiators can be tailored to provide the heat required for a given process. These are relatively simple pieces of hardware whose behavior is well understood as a result of lengthy experience. The matter-free environment can be precisely controlled because there is so little there to start with. It is possible to add whatever is required to suit an industrial process. In short, laboratory-level technology will not be necessary in space!

In general terms, we need a complete dissociation from terrestrial methods. Space processing will differ from terrestrial manufacturing mainly because the operations are achieved by "energy management" rather than by hard tooling such as drop hammers, milling machines, and cranes.

For too long, we have been guilty of thinking of space as a place with a view. Now we must start to regard it as a place in which to work.

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IMAGE LINKS

Figure 5.1: Materials processing in space: Early experiments. (1980). [pdf] NASA, p.12. Available at: http://www.ntrs.gov [Accessed 24 Jul. 2019].

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6

Building Factories in Space

DESIGN OF ORBITAL FACTORIES

Orbital Factories: Configurations

What would an orbital factory look like? As is often the case, the limit is set by our imagination. For simplicity, and because this book is not a textbook in the engineering design of space stations, we will look at four layouts known as the building block, the delta, the big-T, and the truss structure. Other arrangements are possible but these four are sufficient to appreciate how an orbital factory might be arranged. Of course, each will require its own unique characteristics that reflect its manufacturing processes, raw materials used, method of receiving supplies, number of personnel, and so on.

The building block arrangement attempts to minimize structure and subsystems hardware by employing pressurized modules as the structural foundation on which other components such as solar arrays and radiators are mounted by means of booms or robotic arms. Hangars, manipulators, and other external elements are attached to berthing ports which are common to the pressurized modules and truss sections. The normal attitude of this configuration has the pressurized modules in the plane of the orbit, with the long axis of the station aligned vertically to provide gravity-gradient stability and an open approach path for visiting vehicles.[1] Growth occurs by adding new modules, solar arrays, radiators, etc. One drawback of this configuration is that the compact nature of the structure minimizes clearances for access to the available berthing ports. Furthermore, it hinders the removal of an element for reconfiguration or repair because this could require a substantial relocation of modules and external features.

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[1] The gravity-gradient method of holding a spacecraft in a fixed attitude exploits the effect of mass distribution and the gravitational field of the orbited body.

D. Sivolella, *Space Mining and Manufacturing*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-30881-0_6

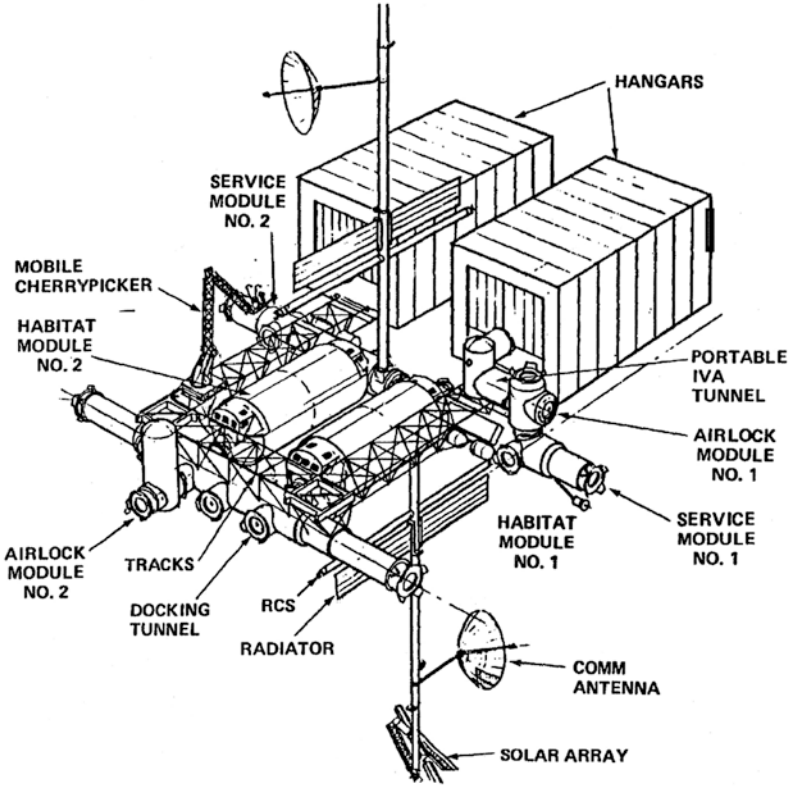

Figure 6.1 An artist's impression of a building block space station configuration. Note the presence of hangar-like facilities (shown as prismatic blocks) that can serve as storage for manufactured products and spare parts, or for assembling complex products.

The delta layout uses a triangular truss structure for independent attachment of elements to maximize rigidity, enhance controllability, and mission versatility. It is approximately Sun-oriented. The solar arrays are mounted on one face of the triangle at a constant angle to the orbit plane in order to eliminate gravity-gradient torque and simplify thermal control. The other two sides support radiators, power conditioning equipment, experiments, payloads, etc. The pressurized modules are mounted in two parallel rows on the truss opposite the solar arrays. The hangars within the triangle use the truss as primary structure and the radiators as part of the skin. Outpost growth can take place by extending the length of the prism or adding extensions to the other two sides to accommodate new modules, hangars, and other elements.

In the big-T configuration, the pressurized modules and most of the operational support facilities are clustered at the lower end of a vertical planar truss while solar arrays, antennas, hangars, and other components are mounted on a

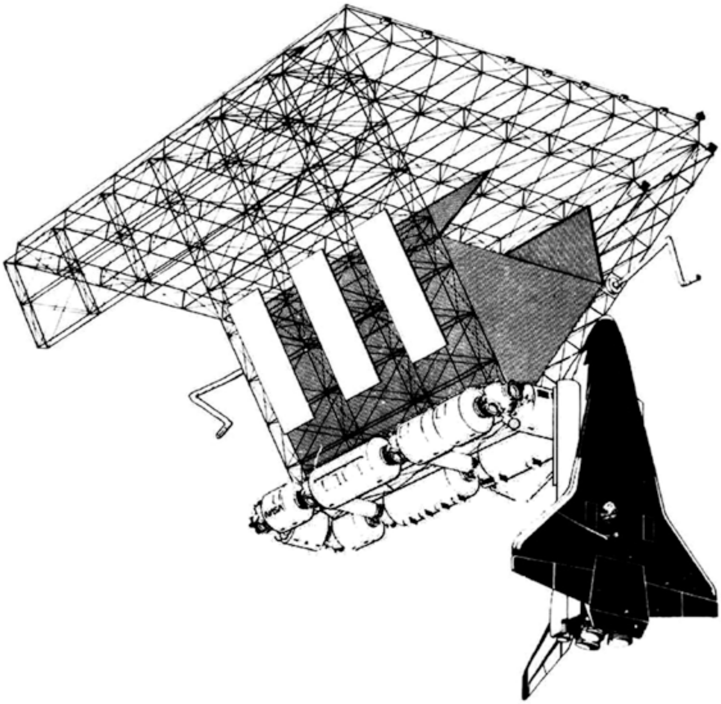

Figure 6.2 An artist's impression of a space station in a delta configuration. The gray panels inside the volume of the triangle double as radiators and hangar walls. The solar panels (not visible) are on the top of the prism, opposite to the collection of pressurized modules.

horizontal planar truss at the top end. Hangars, radiators, and other operational facilities are positioned above the pressurized modules. This configuration enhances rigidity, independence of elements, and versatility of mission. Aerodynamic drag is minimized and a stable gravity gradient is achieved by maintaining the solar arrays parallel to the velocity vector.

A lattice framework can be arranged in a variety of ways, depending on the number of modules and payloads and (in our case) the manufacturing processes which it is to undertake.

Two layouts investigated by NASA in the 1980s were called the Power Tower and the Dual Keel. The Power Tower was a truss structure (called a keel) that was aligned with Earth's gravity vector. A cluster of pressurized modules at the bottom end would stabilize it in the gravity gradient. One or more perpendicular truss sections positioned along the length of the keel would support additional payloads and modules. The Dual Keel was an expansion of the Power Tower in which two parallel keels would be joined by long horizontal trusses to accommodate even more manufacturing facilities.

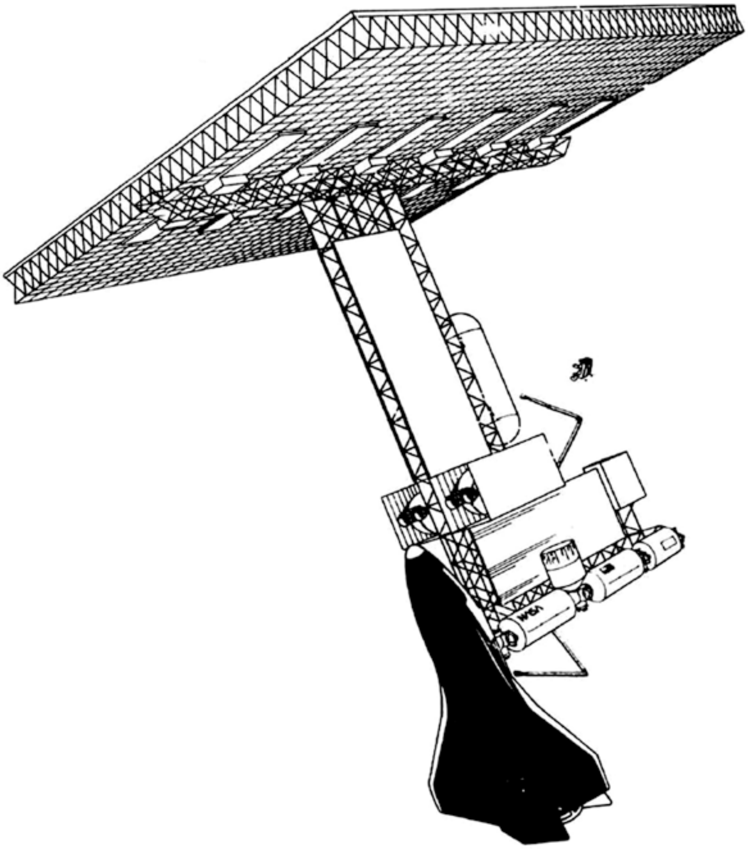

Figure 6.3 An artist's impression of a space station in a big-T configuration. The solar panels (not visible) are on top of the horizontal planar truss and have a limited capability to tilt to maximize the surface area that is in direct sunlight as the outpost travels around Earth.

Orbital Factories: Main Components

What would the main components of an orbital factory be? For a start, the radiators would be prominent. Their presence gives an orbital factory a distinct advantage over a terrestrial manufacturing plant. The second law of thermodynamics is unforgiving, because no process can be 100% efficient. There will always be losses that manifest themselves as thermal energy. The ambient environment of air, soil, and water, serve as a heat sink that absorbs and disperses the thermal energy released by an industrial process. For instance, high temperatures are necessary to melt the iron ingots in a steel mill. Some heat is removed during the cooling process, but much of it is dispersed into the air. Similarly, a coal power

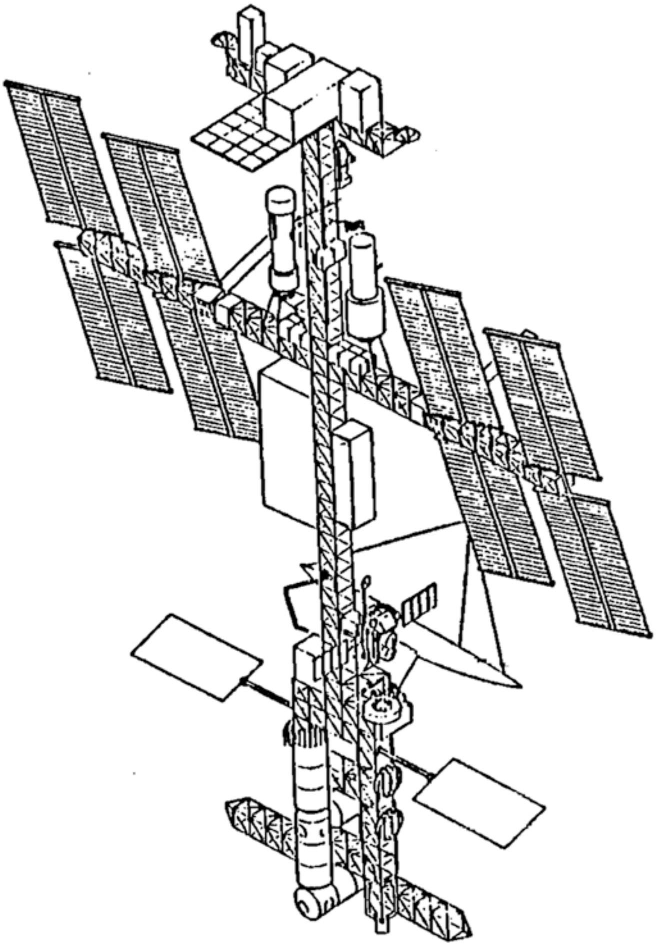

Figure 6.4 An artist's impression of the Power Tower configuration.

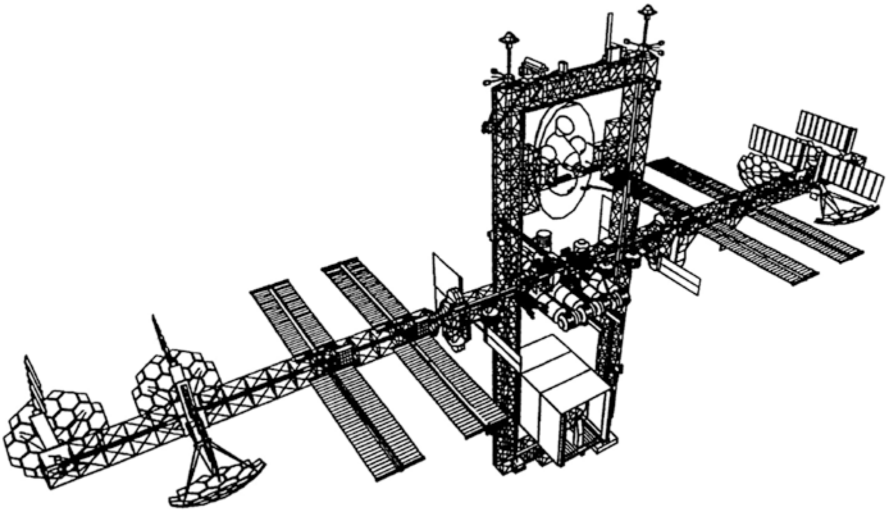

Figure 6.5 An artist's impression of the Dual Keel configuration.

plant requires water to generate high-pressure steam to run the turbines of the electric generators and to condense the steam for reuse. In the condensation phase, the steam's thermal energy is extracted by a heat exchanger which then dumps it into cooling towers or a nearby river. It is not surprising that the sum of all this heat dumping is a contributor to global climate change. Dumping heat in space will not damage the environment because the amount of heat released is insignificant compared to that from the Sun. Because orbital factories will make extensive use of solar furnaces and other heat-generating apparatus, radiators will necessarily be large. Heat pipes and coolant circuits will remove thermal energy both passively and actively and transfer it to radiators. To maximize their ability to discharge heat, radiators will face away from the Sun. Depending on the configuration of the orbital outpost, it might be necessary to use an active pointing system. To shunt as much waste heat as possible, radiators will be exercised until they reach the maximum temperature allowed for their materials. Their large surfaces will be more exposed to damage from micrometeoroids but maintenance robots that work either under human supervision or according to prior programming will swiftly carry out repairs.

Solar collectors will be similarly impressive. As explained in the previous chapter, various manufacturing processes require their raw material to be in a molten condition. Thermal energy for melting can be supplied by electrical power from solar panels or a nuclear reactor, but it will probably be better to use a solar furnace in which sunlight is focused onto the raw material that is to be melted. At our distance from the Sun, two calories per minute fall on every square centimeter of surface perpendicular to the Sun. A parabolic solar collector that is 100 meters in diameter would be able to deliver about 11 megawatts at its focal point. This could easily create a hot spot with an area of 100 square centimeters. The resulting 110 kilowatts per square centimeter influx would be sufficient to evaporate a metal like copper at a rate of 25 pounds per second. The rate for other materials could be higher or lower. It is evident that tons of material could be processed every day! The requirements of a solar collector will strongly influence the orbital parameters. In fact, to avoid interruptions in production it will be wise to place the outpost in an orbit that minimizes the period of darkness. Perhaps the best solution would be one of the Lagrangian points of either the Earth-Sun or Earth-Moon systems. A Lagrangian point is an area of space where the mutual gravitational attraction of two large bodies allows a spacecraft to remain stationary relative to those bodies. A factory in a convenient Lagrangian point would benefit from uninterrupted solar power.

Figure 6.6 shows the typical configuration of a solar collector. It is implemented as a Newtonian parabolic reflector made from several hexagonally shaped panels whose reflective surfaces reflect sunlight and focus it on the raw material in the furnace. Once melted, the material is delivered to the manufacturing plant. A set of struts support the reflective surface and provide a fixed reference system from the vertex of the reflector to the furnace. An active system would provide accurate pointing of the concentrator, to maintain alignment with the Sun as the factory orbits Earth or the Sun. It would also overcome the disturbances caused by people and machinery working in the factory, in addition to external perturbations such as solar pressure, atmospheric drag, gyroscopic torque, and thermally induced displacements.

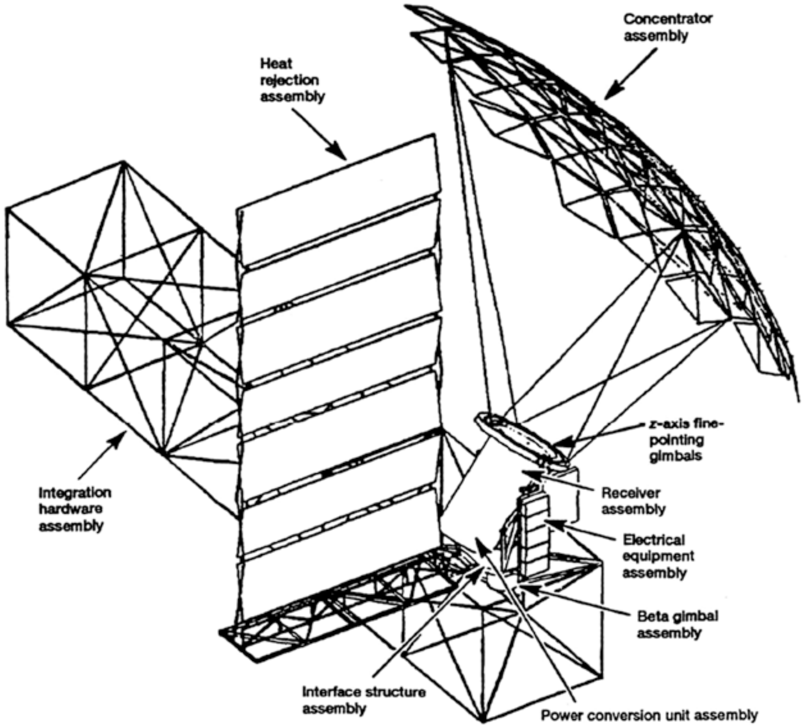

Figure 6.6 A schematic of a solar collector for an orbiting solar furnace.

Orbital Factories: Examples

Manufacturing operations will take place in specialized modules, or platforms such as the Wake Shield Facility of the Space Shuttle, or other apparatus designed to handle specific processes and production of goods. Figure 6.7 illustrates how a manufacturing module might look. This is an extract from patent number 3,534,926 granted by the US Patent Office on October 20, 1970. Despite being over 40 years old, it offers a fascinating insight into the design of what could become a typical processing module in (let us hope) the not too distant future.

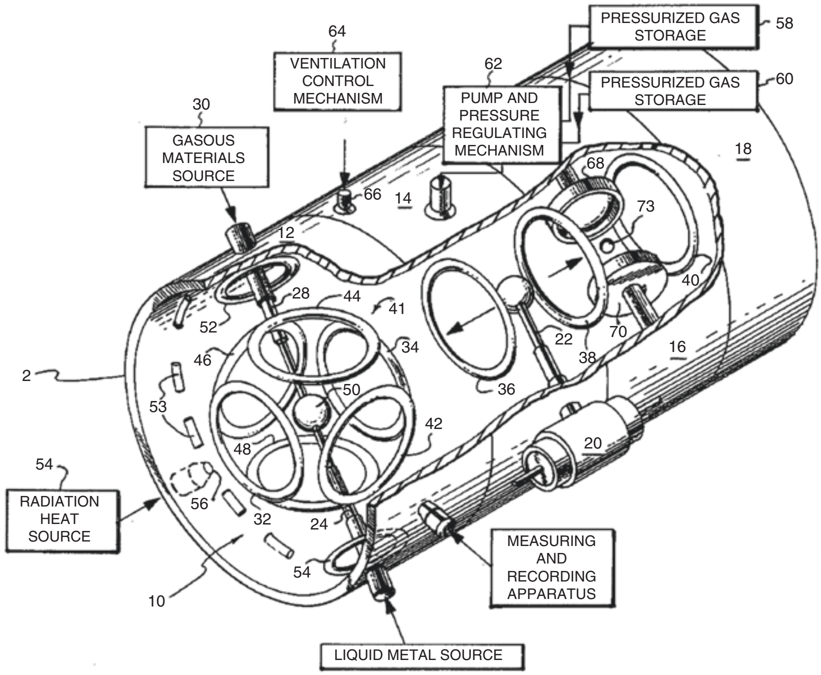

Figure 6.7 A schematic of the space manufacturing machine.

The module would typically be fabricated from a series of cylindrical segments, assembled and sized to suit the needs of the process to be conducted. The casing not only defines the processing chamber, it also offers a means of positioning the various pieces of equipment and tooling for the manufacturing operations. There would be an environmental system to control and manipulate the pressure and composition of the atmosphere. Although not shown, both ends would be capped by an airlock and there would be openings along the chamber walls as required. Based on the size and number of processing areas, the facility could be extended with additional segments. Although a cylindrical module is depicted, sophisticated versions could make use of different shapes to suit individual processes, with intersecting airlocks. Supporting equipment such as containers or bottles for processing gases to provide a particular atmosphere and pressure would be carried outside of the module.[2] One of these is Item 20, defined as a mixing device where various materials could be placed so that at least one of them is heated to a liquid or plastic state. All the contents would then be mixed

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[2] In the zero-g environment, equipment mountings are not required to be strong because their purpose is just to position pieces of equipment, rather than to serve as structural supports to maintain them in place against gravity.

and introduced into the module by a retractable tube [Item 22]. The module also has provisions for other dispensers [Items 26 and 30] for introducing liquids and gaseous materials. Because of the predominant role of surface tension in zero-g, the liquid squirted off such dispensers will collect in the shape of a sphere at the tip of a tube, adhere to it, and move with it unless an external force is applied to separate it. Such an external force could be provided by a number of high-frequency coils [Items 32, 34, 36, 38 and 40] arranged along the longitudinal axis of the module. The coils would generate a force field to center the workpiece and move it in either direction on the longitudinal axis of the module. The coils would be powered by batteries, fuel cells, or solar arrays as appropriate. Inverters in the generation system would convert direct current (DC) into an alternating current (AC) of the desired frequency.

From a position at the tip of a tube dispenser [Item 22], the workpiece would then be moved to the far left, in order to be manipulated by a group of four high-frequency coils [Items 42, 44, 46 and 48] located around the longitudinal axis of the module. By selectively energizing the coils, the workpiece will experience motions and forces designed to shape it into the desired pattern with very precise tolerances. Workpiece kneading could also receive support by low-frequency coils [Items 52 and 54] along the chamber walls adjacent to the group of six high-frequency coils. They generate less rapidly changing fields of force that produce slower manipulation for extended periods. For example, they could blend two or more molten materials inside a sphere positioned in the workstation. Thus, while the high-frequency coils would affect only the outer parts of the sphere, the low-frequency ones would enable the exciting force to penetrate deep inside the sphere. The DC field coils [Item 53] on the periphery of the workstation could induce force fields to precisely shape a liquid workpiece. For example, if the electrostatic and molecular forces in a liquid (cohesive and surface tension forces) act in combination it is possible to make a liquefied material adopt a lenticular or other irregular shape of equilibrium.

Heating apparatus [Item 54] are mounted adjacent to the module, and the energy generated by the heat source is directed towards the workpiece inside the module via an aperture in the wall [Item 56]. The heat source energy could be a focused light beam from solar mirrors, radiation from heating elements in the module, electric arc, electron beam, plasma arc beam, or laser beam. The objective is to heat (or melt) the material. Cooling would be by radiation of heat away from the material to the outside wall. The absorbed heat would then be dissipated by a regenerative cooling system in the module's wall for a controlled cooling rate or by radiation ribs on the exterior surface. Gas bottles [Items 58 and 60] are connected to the interior via a mechanism [Item 62] to control the composition and pressure of the atmosphere in the module. The same regulating mechanism could also be used for retrieving the admitted gases, or what is left, and return them to their respective storage tanks after filtering out any impurities that might have accumulated during the process. A ventilating mechanism [Item 64] exhausts gases to space and communicates the hard vacuum to the interior of the module for the degassing of materials prior to processing.

Another informative example of an orbital manufacturing facility is featured in a 1985 NASA-sponsored study by the Space Systems Division of General Electric. Entitled ‘Space Station Automation Study: Automation Requirements Derived From Space Manufacturing Concepts’, this sought to provide informed technical guidance to the space agency in the use of autonomy and autonomous systems to implement a variety of tasks on a space station, including manufacturing applications. In carrying out this assignment, GE assessed over a hundred potential space station experiments and manufacturing concepts. Subsequent meetings of the NASA Design Team resulted in an instruction to proceed with in-depth development of automation requirements for two manufacturing design concepts, known as the Gallium Arsenide Electroepitaxial Crystal Production and Wafer Manufacturing Facility and the Gallium Arsenide Very Large Scale Integration Microelectronics Chip Processing Facility.

These concepts were chosen precisely because they both require a high degree of automation and hence extensive use of teleoperators, robotics, process mechanization, and artificial intelligence. What is more, they address both processing of raw materials with a sophisticated multi-step process, and are representative of the class of operation, maintenance, automation, robotics, sensor, artificial intelligence and repair challenges to be expected with any type of space manufacturing.

Both manufacturing facilities would be contained in enclosed structures in order to assist in managing waste products and contamination and to facilitate astronaut-tended repairs and equipment upgrades, as well as transfers from one facility to another. Also, the microgravity and vacuum of space would simplify these manufacturing processes over their terrestrial counterparts in which complex power-hungry apparatus is needed to achieve and maintain a vacuum and gravity-induced distortions limit the size of the resulting crystals.

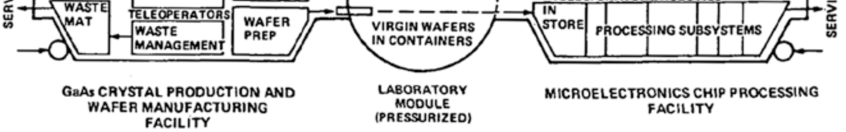

Figure 6.8 An overview of General Electric’s autonomous facilities for wafer and microchip manufacturing.

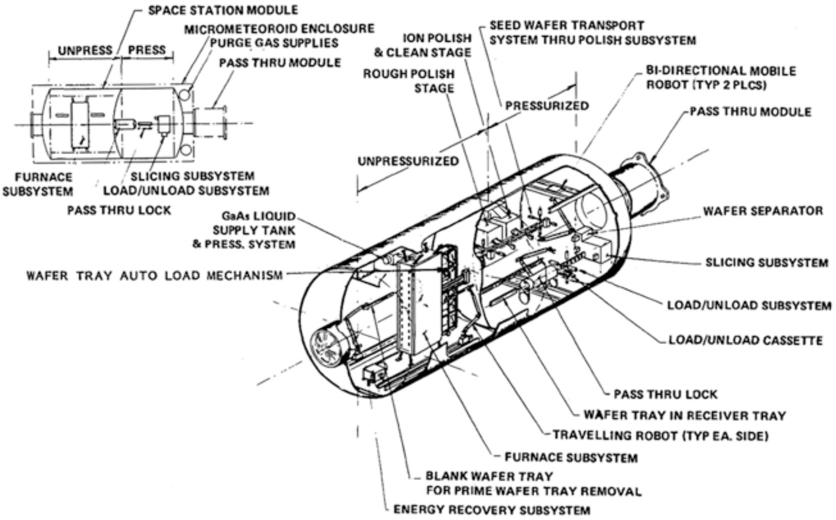

Figure 6.9 An overview of the crystal production and wafer manufacturing facility concept.

Figure 6.8 is an overview of the concept developed for the crystal production and wafer manufacturing facility. It makes extensive use of robotics and other forms of automation and mechanization for almost totally autonomous operations in growing and slicing wafers. The module was to be segregated into an unpressurized section for ingot growth, and a pressurized area for ingot slicing into wafers and subsequent polishing. A central pressure bulkhead would separate the two areas. The transfer of material would be via an airlock. The unpressurized chamber was to house a furnace unit which had 24 small trays arranged in a flat pack, with each tray having room for six pure gallium arsenide seed crystals. This section would be in a vacuum to prevent gaseous contamination and simplify control of the heat transfer that would maintain the furnace at a constant temperature, a parameter that requires constant supervision during the growth cycle. This is accomplished by a Freon-based active temperature control system. On finishing ingot growth, the ingot tray would be pushed out of the furnace into a receiver tray and moved to a temporary storage area. Once a tray was inside the airlock, that would be pressurized and the door opened on the other side of the module. An automatic translator arm would reach into the airlock and lift the ingot tray from the receiver tray (which remains in place) and put it into a cassette ready for handling and transport to the various slicing and polishing stations operated by robot arms. Slicing would be performed using diamond wire cutters. They divide the ingot into three wafers and a seed crystal. This would occur simultaneously at a controlled cut-rate across the full diameter of the ingot. During sawing and retrieval of the wire, separator disk sections would be positioned between the sawn wafer sections. After removal of the cutting tool, the dolly would move along the track to a porthole, where pressure sensitive tweezers (or electro-static head arms) would pick up the sliced wafer sections and put them into a can (like tube-packaged potato chips) together with their separators. The wafers would then be transferred to a rough polishing station, similar in configuration to a horizontal grinder. It would polish the surface to a finish of about 8-12 microns. Then a low-energy sputter-etching or ion-polishing system would apply the final finish to 2-4 microns and remove any debris and other contaminants from the surface. Each polishing station would be self-contained and modularized in its housing. The polished and cleaned wafers would be packaged for forwarding to the microchip manufacturing facility. Meanwhile, the seed would be returned to the unpressurized section to start another growth cycle.

In the microchip facility, the surface of a polished wafer would be manipulated to obtain a wafer containing hundreds of microchips. Generally speaking, microchip fabrication involves a series of complex steps such as film deposition, electron beam lithography, ion implantation, ion etching, sputter deposition, and annealing in order to gradually turn the surface into a collection of detailed patterns. It requires a high degree of control and precision. On Earth it is accomplished through separate stand-alone pieces of equipment, each capable of a specific task. As most of the processes occur in a vacuum (or at low pressure) the microchip manufacturing facility designed by GE would naturally take advantage

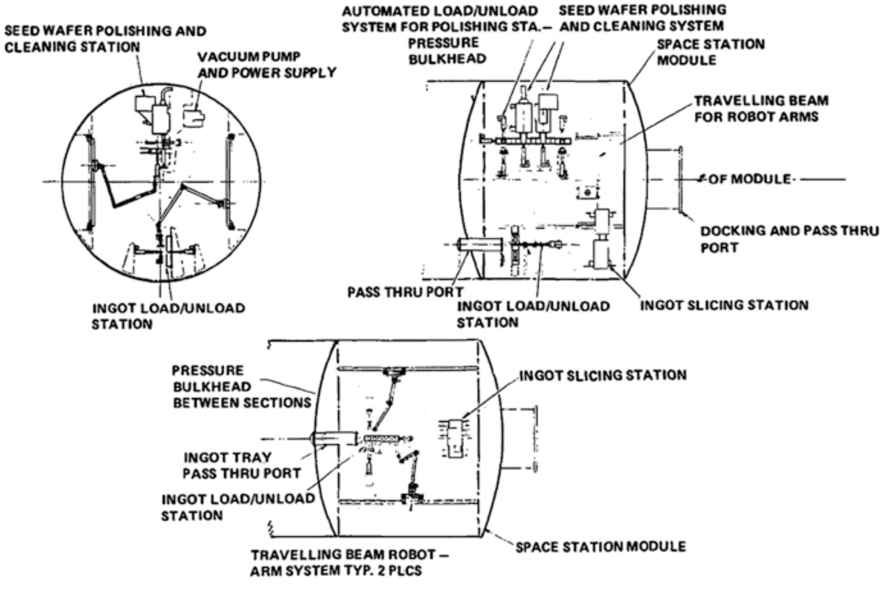

Figure 6.10 An overview of the wafer manufacturing facility pressurized chamber.

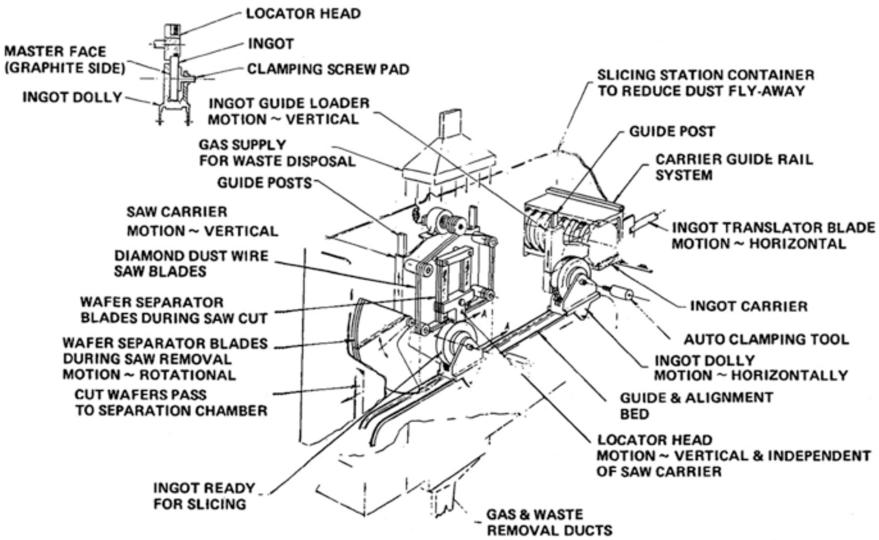

Figure 6.11 The automated raw ingot slicing station.

of its environment, greatly simplifying those subsystems requiring such conditions. The elimination of vacuum pumps and related plumbing would leave room aboard the facility for other apparatus. Furthermore, the microgravity of space would enable the processing apparatus to be much lighter than its terrestrial counterparts.

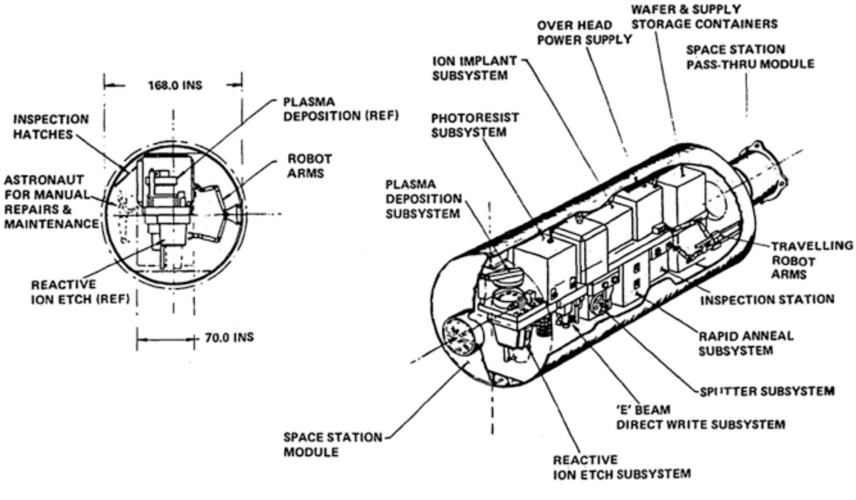

Figure 6.12 The microchip manufacturing facility.

Generally speaking, both GE manufacturing facilities would require self-diagnostic capabilities to troubleshoot problems. Real designs will have to be modular, with clean interfaces to facilitate robotic repairs and replacements. A line of modular components might be developed to simplify the spares requirement. Similarly, standard mechanical and electrical interfaces would be advisable, even though in particular cases that might appear overly elaborate.

ADDITIONAL DESIGN ELEMENTS

Some orbital factories might also sport a rotating section for an artificial gravitational environment to assist one or more processes. Such a rotating section will produce a gravity gradient that starts at zero at the hub and progressively increases in the radial direction. It could be exploited, for example, to integrate fractional distillation with a separation process to sort out solids of different densities at individual points in the distillation scheme. It might also assist manufacturing techniques that operate better in a gravity field but are part of an overall process that is better done in microgravity. The whole purpose of building factories in space is to eliminate the polluting aspects that on Earth inevitably stress the surrounding environment. If research shows that a given product can be more easily produced under the influence of gravity, or if a step in the fabrication of a product works better under gravity, then it will make sense to add a rotating section for that purpose.

One type of process that might benefit from a degree of gravity is that requiring degassing of the material in the liquid phase. In weightlessness, buoyancy forces are not available and bubbles do not rise to the free surface of a liquid in order to escape. The elimination of gas bubbles from the molten material could pose a severe problem. However, the molten material can be subjected to acceleration to displace gas bubbles. The centrifugal force inside a rotating section will cause bubbles to migrate away from the axis. The total gas bubble, as well as the spinning free-floating material, will adopt a shape that depends on the angular velocity, the volume, the viscosities, densities, and surface tensions involved. The stability of the system is also of importance. In fact, this is an excellent example of how we can achieve the needs of manufacturing by turning on and off phenomena that occur only in zero-g or reproducing phenomena that occur only in a gravity field. This degree of customization is rarely possible on Earth, where gravity is ubiquitous.[3]

In any case, a rotating section will be a necessity for the well-being of the people in the orbital factory. Working in space will be an exciting experience, but

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[3] The presence of large rotating section will introduce attitude control problems owing to gyro moments and torqueing during start, stop, and rotation.

on ending a shift a worker will not be able to return home unless it is to a separate habitat close by. In all likelihood, life on an orbital factory will resemble that on an oil rig, in that there are private quarters as well as communal areas for recreation and socialization. In view of the detrimental effects of weightlessness on the human body, it would be reasonable to have one part of the facility reproduce a gravity field suitable for long-term residency, so that the workers need not spend several hours per day on exercises designed to mitigate loss of bone and muscle mass.

An orbital factory will be a complex aggregate of modules, truss structures, huge solar collectors and radiators. It will be a living entity, changing, morphing as a better understanding of space manufacturing is gained, as manufacturing needs change, as new modules are added and as old ones are discarded, transformed into warehouses or stripped for spare parts. They will need the flexibility to allow them to serve many different manufacturing processes and products.

For various reasons, orbital factories will not resemble their terrestrial counterparts. Firstly, on Earth the environment required for an industrial process must be reproduced inside the enclosure of the manufacturing plant. In space, it is the other way around. In fact, the industrial process is designed to exploit the existing environment.[4] Another fundamental difference is that in terrestrial factories the workers are an integral part of the manufacturing process and they work alongside sophisticated robots on the factory floor. In space, activities will be performed under the highest level of automation and humans will mostly carry out supervisory functions. In fact, automated machinery and robots will accept the raw materials, process them, and fabricate a useful product. This will be particularly so if most of the manufacturing occurs in a vacuum. Depending on the process and the product, it might be preferable to undock the processing module to carry out its work as a free-flying platform, and later retrieve it to offload the finished products and load raw materials for the next run.[5] Maintenance robots will intervene in the event of a technical problem. By monitoring diagnostics, they might even act to pre-empt a fault. Only for the most demanding of repairs would a human response be required.

In space, the concept of a factory floor will also be different. A floor is a surface that supports and locates a machine relative to other equipment and lets materials and personnel move from place to place as appropriate. Gravity and frictional forces retain machinery in position. In zero-g, maintaining a position is unnatural

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[4] The exception would be in the case introducing artificial gravity, which would constitute a manipulation of the existing low-g environment.

[5] Such a condition would occur if the manufacturing process were significantly disturbed by spurious forces caused by crew movements or by other surrounding manufacturing activities.

because an object, even if in a condition of neutral stability, can experience an infinite number of tumbling modes. Consequently, although a floor in space is not required, the need for positioning and handling materials and equipment inside and outside the manufacturing facilities remains. The science and technology of robotic manipulation in the space environment is a well-established discipline, learned through no less than four decades of operating robotic manipulator systems on the Space Shuttle, International Space Station, on Mars rovers, and even the Robonaut2 humanoid robot that is now undergoing trials on the International Space Station. This experience will provide the basis for the development of new robotic systems customized for working around-the-clock in an orbital factory. In view of the time and cost involved in developing complex robotic systems, it would be wise to make them as versatile as possible. They should be able to handle different materials, carry out various functions, and be capable of working inside and outside of the facility.

As we can expect orbital factories to reach a considerable size, they will require an internal transportation system to move raw materials, resident staff, and finished products both inside and outside of the factory units and habitats. A system of carts that run on rails and are remotely operated would probably suffice. There is already a simple cart on the International Space Station operating as the Mobile Base System.

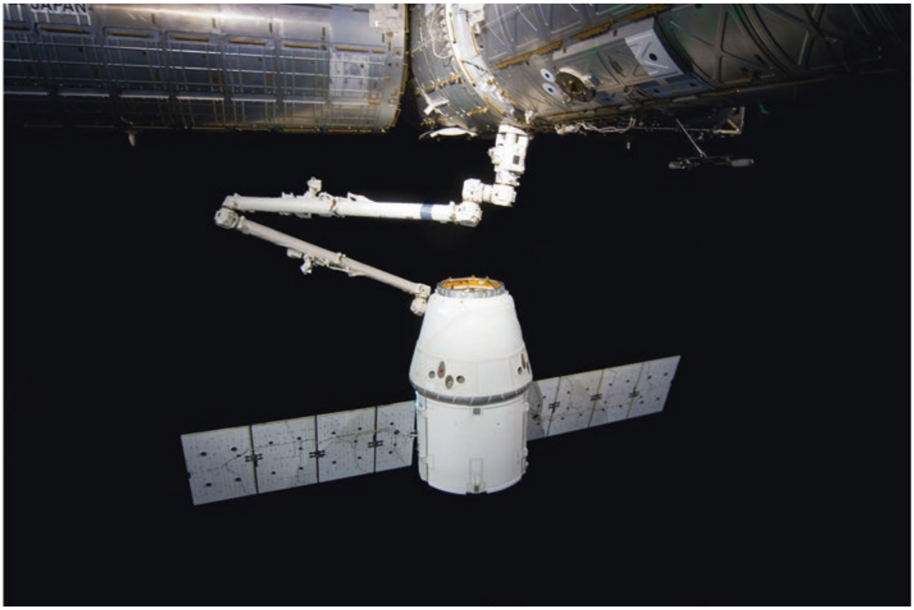

Figure 6.13 A global view of the Robotic Manipulator System of the International Space Station as it is about to release a SpaceX's Dragon capsule.

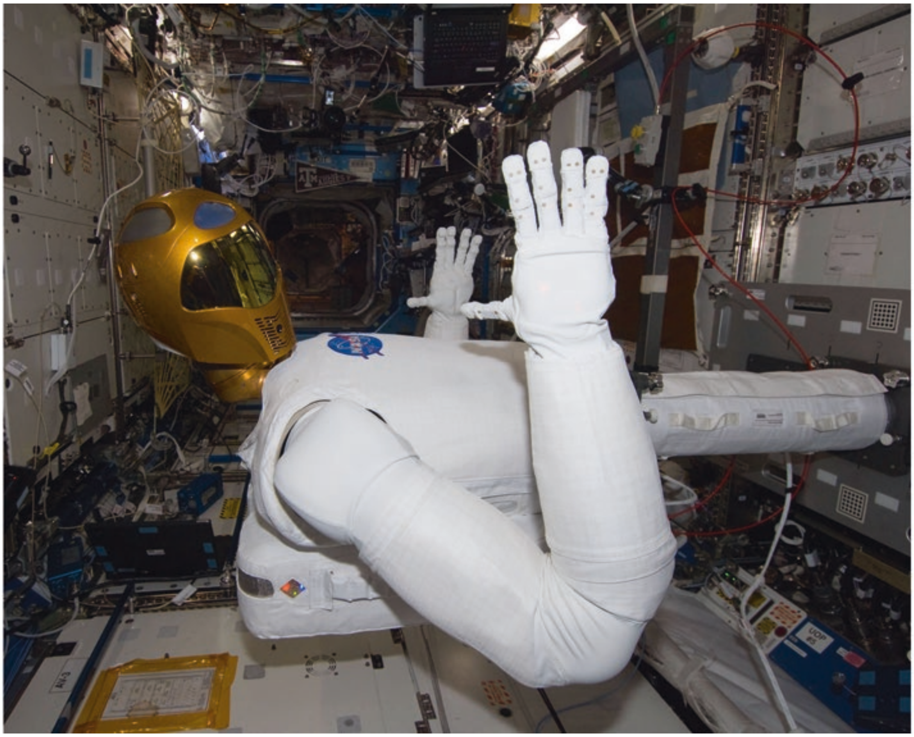

Figure 6.14 The dexterous humanoid Robonaut is now a permanent resident of the International Space Station.

Pipelines will transport molten materials by exploiting controlled wettability and capillary action. Figure 6.15 shows a spherical chamber in which the movement of the molten material is achieved by the high wettability of all surfaces. A perforated inner sphere and its associated capillary effect will ensure transport of the material toward the outer sphere wall and the mold passage. Movement is supported by the pressure-controlled formation of a bubble in the central space to squeeze the molten material out of the perforated sphere. Due to surface tension forces arising on the perforations, the gaseous bubble will not cross the inner sphere. In addition, the bubble will absorb vapors from the melt as they travel to the liquid-gas interface.

Depots to store raw materials, spare parts, and finished products could take the form of platforms on the truss structure or anchored to other elements. A prototype for such storage could be the lightweight platforms called Express Logistics Carriers that were mounted on the truss of the International Space Station to store spare parts and experiments.

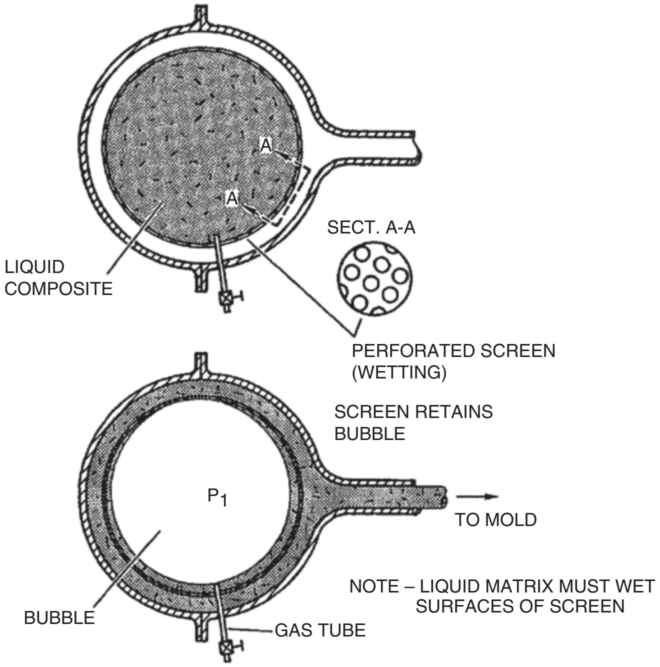

Figure 6.15 An example of a spherical melting and dispensing unit.

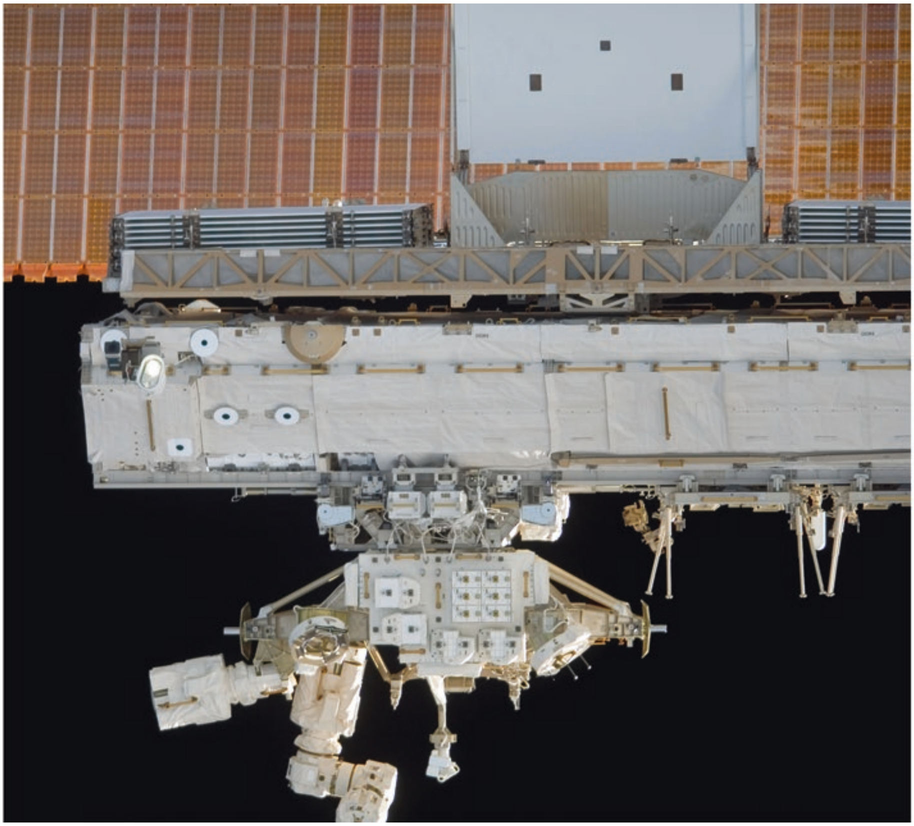

Figure 6.16 An overview of the Mobile Base System of the International Space System, which moves the robotic arm and astronauts during extravehicular activities.

Figure 6.17 Two platforms for storage of spare parts placed either side of the truss structure.

In the International Space Station, we have a substantial amount of experience in building and operating a cluster of pressurized modules as laboratories and habitats. But the sizes of those modules, the elements of the truss structure, and the platforms were limited by the dimensions of the Space Shuttle's payload bay as well as by the mass the Shuttle could lift into orbit. In the post-Shuttle era we have reverted to using rockets, but new powerful ones are becoming available. Larger, heavier modules will become possible but they will be constrained by the fairing which protects a payload during its ascent through the lower part of the atmosphere. One way to increase the size of pressurized module is by employing inflatable technology. If the idea of using balloons in space appears strange, consider that in the 1960s NASA investigated the role of inflatable structures in the deployment of a space station. More immediately, Project Echo developed passive communications satellites. These were launched in 1960 and 1964 as Echo I and Echo II. Once in orbit, they inflated to the astonishing diameters of 30 and 41 meters, respectively. Their skin was a thin sheet of metalized Mylar material that reflected radio signals. After a long hiatus, inflatable technology for space applications was investigated in the mid-1990s when NASA considered its role as a large habitation module for the crew of the forthcoming International Space Station. They would live and relax in this TransHab while off duty. It was to consist of a lightweight cylindrical core of graphite-composite 3.4 meters wide and 7 meters long (these dimensions being dictated by the payload bay of the Space Shuttle), and be surrounded by a shell of material carefully wrapped around it in the manner of a folded parachute. In-situ, the shell would be inflated to a diameter of 8 meters. This would yield thrice the volume and over twice the storage space for a cost and weight comparable to a traditional aluminum structure.

The interior of the TransHab would be organized on three levels to incorporate a fully equipped galley, multiple soft storage arrays, six individual crew quarters, the apparatus for the environmental control and life support systems of the station itself, exercise equipment, a bathing area, and apparatus to monitor the health of the crew and deal with emergencies.

The inflatable shell was a significant technological achievement. It was to be 40 centimeters thick and comprise over 60 layers arranged as five major subassemblies. As Figure 6.18 shows, the inner wall would be non-flammable, puncture resistant, and offer good acoustics. It would protect a multi-layer assembly of bladders that would provide a redundant primary gas containment mechanism. A bleeder cloth was to be placed between the adjacent pairs of bladders to prevent contact, eliminate abrasion, and make a cavity between the bladders. The pressure within each bladder would be monitored in order to detect and locate leaks. A woven restraint layer would enable the bladders to resist an internal pressure of up to 4 atmospheres. The structure would be protected from micrometeoroid impacts by a debris protection system consisting of multiple layers of ceramic fabric separated by open cell foam and a Kevlar fabric debris catcher. In the event of an

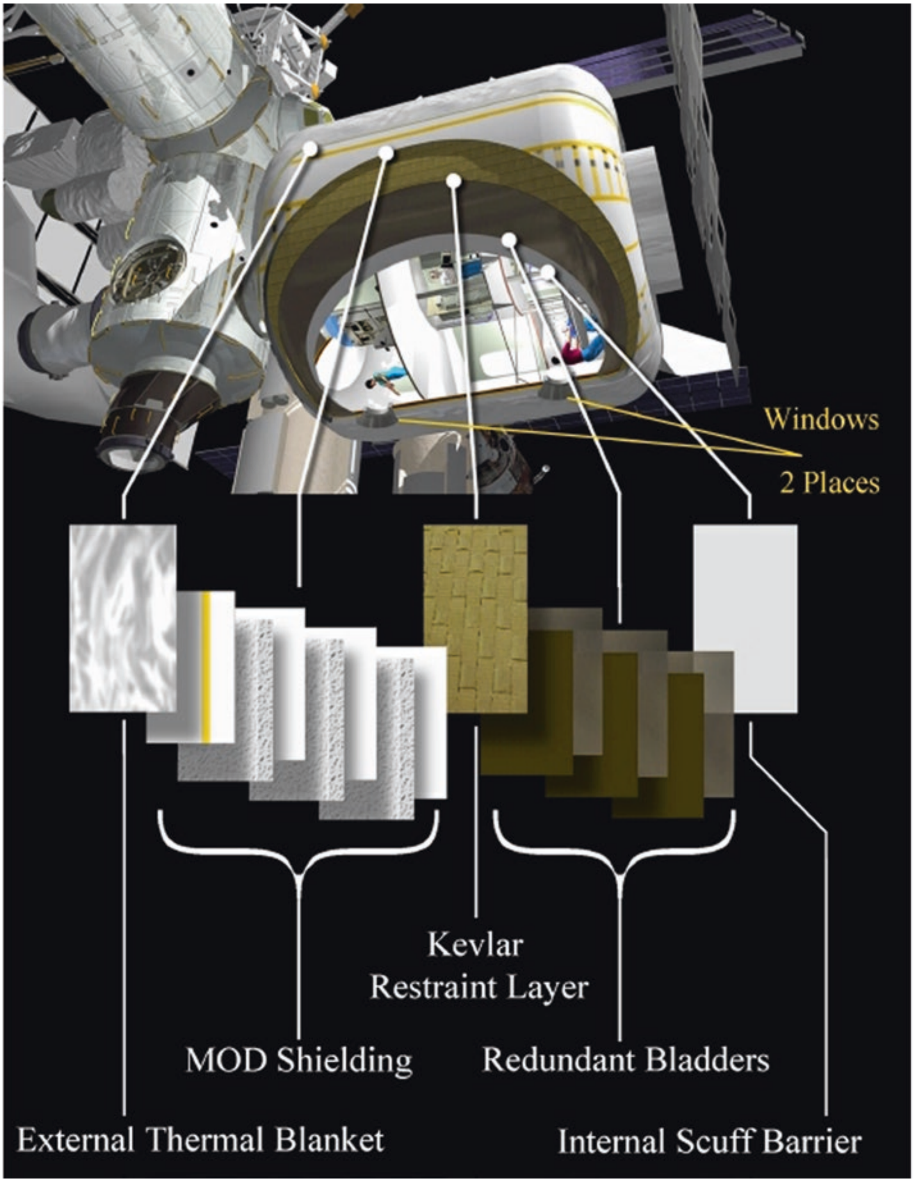

Figure 6.18 An exploded view of the TransHab layers.

impact, the particle would be progressively slowed and broken into smaller and slower particles by each ceramic and foam layer. By the time a fragment reached the restraint layer, it would have lost so much energy that it would halt. Multiple layers of Nylon and Mylar were to provide thermal protection. A single-sided aluminized Beta glass fabric on the exterior would protect against the atomic oxygen in low orbit that is capable of degrading materials.

Figure 6.19 The Bigelow Expandable Activity Module (BEAM) in its current position on the International Space Station (highlighted with a white circle). Although small in comparison with other modules, it is the forerunner of much larger inflatables that will expand our capability to live and work in space.

Trials validated the inflatable concept but budgetary constraints obliged NASA to mothball the project. However, the technology was not lost. Indeed, it was bought by Bigelow Aerospace, a start-up company based in Las Vegas, Nevada, established by Robert Bigelow, the self-made millionaire owner of the hotel chain Budget Suites of America. Why? Bigelow Aerospace's ambition is to build and sell space stations made of inflatable modules. They might even be used on the Moon, either out on the surface or inside caves. The company has already made significant progress. In 2006 and 2007 it launched the Genesis I and II inflatable modules using Russian Dnepr rockets.[6] The 4.4 x 2.54-meter modules are still in orbit and in good health. In 2012 the company signed a contract with NASA to provide a commercial demonstrator of an expandable habitat module for temporary attachment to the International Space Station. Named the Bigelow Expandable Activity Module (BEAM), this would help NASA to address key elements in future deep space and surface missions. Launched in 2016 aboard a SpaceX

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[6] The Dnepr rocket is relic of the Cold War. It was developed as a nuclear ballistic missile for launch from a silo. After the fall of the Soviet Union, it was modified to carry light payloads into space.

Dragon spacecraft, BEAM was successfully transferred to the ISS and inflated. It has been performing so well that its initial 2-year mission has been extended to 2028, when the ISS itself is scheduled for decommissioning. Being only a test, BEAM had a volume of just 16 cubic meters. The B330 module that the company is developing will inflate to an astonishing volume of 330 cubic meters. In comparison, a typical ISS module has a volume of 160 cubic meters. The B330 will have its own propulsion, power generation, life support and docking mechanisms to enable it to serve either as a stand-alone space station or as part of a larger structure. Bigelow Aerospace will therefore be well positioned to supply habitable facilities to commercial manufacturing-in-space ventures.

FACTORIES ON CELESTIAL BODIES

The Moon will also be an excellent location for industrial operations. It offers all the characteristics of the space environment except zero-g. Factories on the Moon (and in due course on other planets) will probably resemble Earthbound factories because they will be on firm surfaces and will have gravity. Again, they will employ hectares of solar panels for electricity generation, radiators for heat dissipation, and collectors for solar furnaces. The production facilities will be underground, or at least partially buried and covered by a thick layer of regolith for protection from cosmic radiations, micrometeoroids, and thermal control. In the vacuum of space, the thermal loads on a structure can only be dissipated by conduction or radiation, as convection needs a fluid for heat transport. Conduction and radiation are not effective in dissipating heat from a large thin-walled structure and the 300°C diurnal variation on the surface of the Moon will induce mechanical loads sufficient to cause large distortions, possibly even structural collapse. If the facility is protected by at least a covering of lunar soil, this will alleviate the extreme temperature fluctuations and simplify the design of the structure and the regulation of its internal temperature. It has been calculated that a shield of regolith just 10 centimeters thick would reduce the thermal fluctuations by 99%.

An interesting departure from terrestrial manufacturing plants is that a factory on the Moon will likely be close to the mine from which the raw material originates. On Earth this is hardly ever the case, because siting a factory depends on critical aspects peculiar to its operation. For instance, a steel mill is usually located near a source of coal rather than near an iron mine because the former is used in larger quantities and it will be cheaper to locate the plant near the coal rather than the iron mine. Also, manufacturing usually requires using different raw materials that are rarely found in a single place. In any case, mines tend to be in remote, difficult-to-access places that are inappropriate for a manufacturing plant. As noted in Chapter 2, the resources of the Moon are widespread rather than being concentrated in ore deposits. In any case, to simplify the logistics of transporting raw material, it would undoubtedly be more sensible to locate mines and manufacturing plants near each other. Figure 6.20 shows how a lunar manufacturing plant might look.

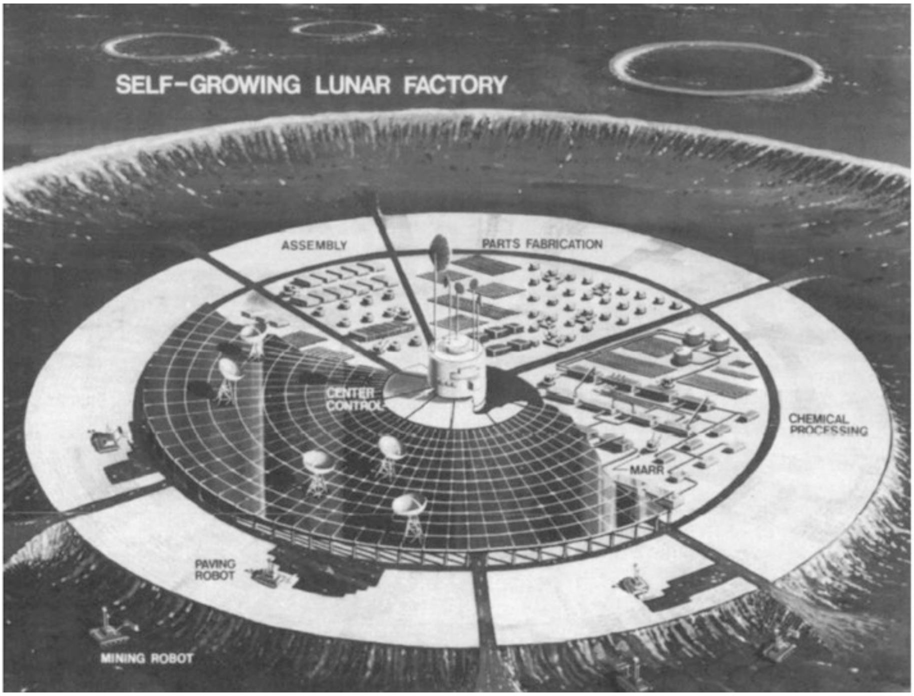

Figure 6.20 An artist's concept of a prospective lunar manufacturing facility.

The facility has a circular shape for the smallest ratio of perimeter to surface area and the shortest interior transportation distances. It is split into two identical sections, each with a chemical processing plant, a sector for fabricating parts, and an assembly area for the final products. Notice the presence of paving robots, used to forge a firm foundation for installation of the equipment and infrastructure. This can be achieved by melting raw material and lunar soil at about 1,800°C and then allowing it to cool and solidify to a very hard and strong material. If cooling occurs in a matter of tens of minutes the liquid basalt will be quickly quenched and become a polymeric glassy substance that is strong but brittle and therefore subject to cracking.[7] If instead the molten basalt is allowed several hours to cool

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[7] Basalt is plentiful on the lunar surface, is easy to work, and offers good structural strength. It is ideal for a solid, long-lasting, clean surface to support road traffic and manufacturing plant machines and apparatus.

from a full liquid state to hard solid below 1,460°C it will anneal into a crystalline material that is much less brittle. This method, however, requires more energy and time. Should the first option be selected, the pavement will be divided into slabs about 1 meter square to limit propagation of fractures. The slow-cool method is able to make a continuous surface. Given the low gravity and the likely surface loads from the facility, a pavement 3 centimeters thick would suffice. Several means of robot operation would be possible. For instance, the robot could scoop out a hole of the appropriate dimension, ingest the soil and melt it in an internal furnace, then drain the basal magma back into the hole to neatly fill it. The furnace could operate by resistance heating, arc heating, induction heating, or, even better, direct sunlight.

In the facility depicted, resources are strip mined in a circular pit surrounding the manufacturing area and the material is delivered to large hoppers arranged along the entry routes to the chemical processors. The recovered volatiles, refractories, metals, and non-metallic elements are sent to the fabrication sectors for the manufacture of individual parts, tools, electronic components, as appropriate. The assembly sectors will combine the parts into complex products. The unwanted waste and residue from the processing sectors will be loaded into hoppers and returned to the excavation pit as landfill. In this way, new ground is reclaimed ready for paving to allow for future radial expansion of the manufacturing plant.

On Earth, factories tend to specialize in manufacturing specific products. On the Moon (and indeed on the asteroids and any other planetary body) a facility in which the mine and manufacturing plant are co-located must define its range of products in terms of the resources that are available in its immediate vicinity. Of course, this is not to say that the terrestrial approach cannot be pursued, but separating the mining from the manufacturing would require a more complex arrangement for the delivery of the raw material. This could use trucks and trains, or hopping spacecraft, or a mix of the two.

The manufacturing processes and equipment used on the Moon will be similar to those used on Earth, modified for one-sixth gravity. This will have both advantages and disadvantages in terms of equipment sizing, depending on the intended process. Even the high terrain at the lunar poles cannot provide sunlight for 100% of the time, although it comes close. And a site away from the poles will mean a fortnight-long period of darkness. This will inevitably mean the establishment of nuclear plants for the thermal energy and electricity needed to run a factory continuously. We will look at nuclear in space in the next chapter, as we examine current progress in developing civil reactors that could be readily adapted for safe use in space.

When it comes to asteroids, the easiest option would be to mine the asteroid and transport the raw materials to a factory in Earth orbit.

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7

Making it Happen

THE ROAD TO A WORTHY SPACE PROGRAM

In his book *The High Frontier*, Gerard K. O'Neill proposed that the long-term goals of activities in space ought to be "ending hunger and poverty for all human beings; finding high-quality living space for a world population; achieving population control without war, famine, dictatorship or coercion; increasing individual freedom and the range of options available to every human being; unlimited low-cost energy available to everyone; unlimited new material sources, available without stealing or killing or polluting."

Quoting this in Chapter 1, I said that whilst it sounds a lot like wishful science-fiction thinking it is not beyond our current capabilities to develop a space program with the potential to bring to fruition some of the long-term goals listed by O'Neill, or to put that another way, a space program that is worth undertaking. The preceding chapters have provided food for thought regarding the availability of raw materials on neighboring celestial bodies such as the Moon and the Near-Earth Asteroids. We have reviewed the fundamentals of mining and processing extraterrestrial resources, and how manufacturing might be undertaken in the weightless environment of space and the low gravities of celestial bodies.

It cannot have escaped your notice that none of these technologies currently exists outside of technical publications and popular science magazines. In fact, there is no off-world extraction of resources taking place, let alone any meaningful glimmer of manufacturing products for use on Earth. I find it rather disconcerting that little effort has been committed to understanding how we might move from having no off-world resource extraction and manufacturing to having those activities regarded as integral to our society and economy. It is like wishing to spend your holidays in a destination of your liking, perhaps one you have long dreamed

D. Sivolella, *Space Mining and Manufacturing*, Springer Praxis Books,
https://doi.org/10.1007/978-3-030-30881-0_7

of visiting, but without planning your trip. Even science-fiction productions, both on paper and on screen, are a let-down in this sense because they are set in a future in which humans have colonized the Solar System, if not the entire galaxy. So while you can enjoy stunning graphical representations of a society living in gargantuan space stations and traveling across the vastness of space on board AI-filled spacecraft, no effort is made to explain how that situation came about. There is such a gaping divide between the reality of today and such wishful visions of tomorrow that we need to bridge it in a feasible, realistic, and sustainable way. Equally important is that we do it for a truly meaningful cause. As noted in closing Chapter 1, a reasonable, compelling, and influential motivation is to use the resources of space to help to "preserve the magnificence of our planet's biosphere and live in harmony with its countless ecosystems". If we do not expand into space for a genuine practical purpose, then space exploration will inevitably be relegated to a small appendix in the history books of human achievements.

The demise of the Apollo program, which ended after only six trips to the surface of the Moon, was due to the absence of a compelling reason for such missions. This is why this section is called The Road to a Worthy Space Program. The "worthiness" comes from seeking to bring about a space-based manufacturing industry that makes use of space resources for the benefit of humankind on Earth by alleviating the stress we are imposing on its biosphere, because it is the only world capable of supporting a human civilization.

Earlier chapters looked at the technology and primary ingredients of space-based mining and manufacturing. Now we shall review a possible path to such a future.[1]

ACCESS TO SPACE: THE CHEAP WAY

Any means of transportation, whether a simple canoe or a jet-liner, will be designed for reusability, as it would not make sense otherwise. Given the effort that goes into designing and building a vehicle, purchasing the raw materials, labor, manufacturing facilities, and so on, no one would seriously contemplate discarding one's means of transportation after a single voyage. Nevertheless, for the last six decades the space industry has worked in this manner, launching expensive rockets without recovering and reusing them.

This is a lasting legacy of the Cold War that obliged the USA and the USSR to create intercontinental ballistic missiles for nuclear warheads and rockets to

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[1] Although the illustration of a path conjures up the notion of a serialized progression of achievements, where a new step is pursued only after the previous one has been completed, you will see that throughout this chapter the concept of a "path" is used in a broader sense of engaging in a parallel or concurrent way a variety of undertakings, all aimed towards the same goal.

launch satellites for reconnaissance, early warning, and communications. Launching things into space even served a propaganda purpose. With time and money at a premium, rocket development was directed towards expendable launchers because that was the faster option. If you consider that a rocket engine is essentially a device designed to tame in a controlled fashion the energy of a powerful explosion, then it is easy to appreciate how rocket design is indeed rocket science! Making them reusable, while not totally unfeasible, would have required expenditure of time and money that were not available at a time when the superpowers were trying to outdo each other at an accelerating pace. Except for the Space Shuttle, which introduced a high degree of reusability (albeit achieved only by costly maintenance), the use of expendables has continued.[2] In fact, despite greater design experience and advances in technology, rocket manufacturers have chosen to retain their earnings rather than invest in R&D programs to fashion a reusable product.

That was the case until Space Exploration Technologies Corp., widely known as SpaceX, and Blue Origin became rocket launch service providers. I am sure neither company requires an introduction, because they are routinely featured in the media. Each is backed by a billionaire with his own vision for the future of humans in space and the determination and personal wealth to make it happen.[3] Although their goals are somewhat different, both companies have set in motion a revolution in the launch service industry by making their rockets recoverable and reusable.

SpaceX's offering is the Falcon 9, a two-stage rocket that has already completed dozens of launches for commercial and governmental customers. This rocket is put together in a lean manufacturing process that minimizes operating costs and thereby reduces the price to the customer relative to other providers. For example, to deliver 5.5 tonnes to geostationary orbit the Falcon 9 is priced at $62 million in its reusable mode, whereas to deliver 4.9 tonnes using the smallest of United Launch Alliance's Atlas V rockets would be a minimum of $109 million. The triple-core Falcon Heavy in reusable mode could deliver 8 tonnes to that same destination for $90 million.

Another compelling argument is that the first stage of the Falcon is capable of flying back and landing on a pad near the launch site, or on an autonomous barge at sea. After a brief period of refurbishment the stage can be flown again. Customers shopping for a Falcon 9 launcher with a previously flown first-stage can gain

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[2] In recent times, emerging space powers such as China and India have grown their own domestic access to space via the same pattern.

[3] SpaceX is headquartered in Hawthorne, California, and under the leadership of Elon Musk has the strategic objective of colonizing Mars. Blue Origin was established by Amazon CEO Jeff Bezos, is headquartered in Kent, Washington, and is seeking to transfer our heavy and polluting manufacturing industries into space.

further savings. The company is working towards making 10 flights without refurbishment and 100 with refurbishment. In 2017, SpaceX started routinely using recovered first stages and is rapidly approaching the point at which it will almost cease to make new ones. The Falcon Heavy is basically a Falcon 9 with an additional first stage strapped on either side, all of which are recoverable and reusable.[4]

Figure 7.1 A SpaceX Falcon 9 first stage is about to land after another successful launch.

And there is more because the company is enthusiastically developing a launcher to dwarf everything built so far, including the mighty Saturn V of the Apollo era. It consists of a first-stage named Super Heavy and a second-stage named Starship.[5] In its initial configuration it will be able to deliver 100 tons into

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[4] The three first stages of the Falcon Heavy are slightly different from a typical Falcon 9 first stage, because their structure was strengthened in specific areas to account for the additional dynamic forces imposed by having three thrusting stages transferring loads to each other.

[5] SpaceX has the irritating habit of not sticking to names. This is especially so with this rocket, whose name has changed several times. A different name might be in use by the time you read this book, but it will be the same vehicle.

low Earth orbit. It will be fully reusable. Its capabilities are designed to enable Musk to pursue his desire to create human settlements on Mars.

Blue Origin is also increasing its pace with the development and testing of their small New Shepard rocket and crew capsule, both of which are fully reusable. These were designed to serve commercial markets such as flying ordinary people who want the thrill of a sub-orbital ride to an altitude of 100 km and experience weightlessness for several minutes, and carrying scientific experiments for research institutions and national space agencies. The larger, fully reusable two-stage New Glenn will be able to deliver up to 45 tons into low Earth orbit.

What SpaceX and Blue Origin are doing is genuinely game-changing, as they are bringing to the table reusability and heavy lifting capability at a fraction of the price currently requested by other launch service providers.

To understand why this is important, let us consider what I see as the “launcher oppression”. Expendable rockets are costly to operate, as the material and financial resources invested in manufacturing such a vehicle have to be fully absorbed by just a single mission. This translates into a lofty price tag because it must account for the overall cost of manufacturing the rocket (remember a brand new rocket is built every time, from scratch) plus the earnings the company seeks to achieve. As launches are infrequent and building a rocket is time-consuming, neither the launch provider nor a customer wants to see their investment end in a blaze of fire on the launch pad or during ascent. Even if used only once, rockets must be sufficiently reliable to assure mission success as defined by the requirements of the customer. If the launch fails, then the payload is most likely lost along with the mission and the expected returns. Of course, a new rocket and spacecraft can be built but it is not as simple as it might sound. For a commercial or military payload new funding will likely be secured, but the prospects will be grim for a scientific mission such as an interplanetary explorer. Even if a new spacecraft is built, there is the issue of finding a launch provider with an open slot in their schedule. Usually, this entails waiting years before the customer has a second chance to send their payload into space. High reliability is therefore an extremely important factor in determining the overall cost of a launch.

This has far-reaching implications for the design of spacecraft. All hardware that is destined for space is designed and built to operate perfectly. Yet failures do occur. Why not repair them in space? With few launches available per year and at such high cost, there is simply no profitable market for a spacecraft capable of servicing and maintaining orbital assets by, for instance, refueling or conducting hardware repairs. If a satellite suffers a failure, the lack of an orbital breakdown recovery service means that asset has to be written off, even though the fault was repairable.[6] This translates into costly and time-consuming development and

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[6] The only time that on-orbit repairs were conducted was on Space Shuttle missions.

testing of a spacecraft to ensure it will operate flawlessly throughout its planned life in space. In the world of spacecraft development there is no such thing as a prototype. The spacecraft that is built is the prototype and also the real thing. For interplanetary missions, planetary rovers, and space-based telescopes the situation is even more stark. Because of the lack of cheap rockets and the scarcity of launch opportunities, for every probe or telescope selected for construction, tens of other projects are discarded because there are funds only for a handful of missions. For interplanetary spacecraft an additional complication arises from the stringent requirements imposed by a launch window that will take advantage of planetary alignments or encounters that can significantly assist a probe in its voyage, sometimes shortening the journey time by years. Often it translates into a considerable reduction in the propellant requirements of the mission, allowing for an increase in the scientific payload. In the case of a launch failure, supposing that a replacement probe can be built, the next available window might not be as favorable as the intended one. Mission planners may have to review the mission objectives in order to accommodate the restored propellant requirements. And the travel time might be so lengthened as to increase the likelihood of a malfunction crippling the vehicle in transit.

To summarize, the lack of reusable and cheap launch services has greatly hampered space development right from the start of the Space Age. It has created a Catch-22-like situation. Because launching a spacecraft is expensive and there are not many launch opportunities, a small number of spacecraft will be built. This is typical for scientific missions funded by taxpayer money. A limited number of spacecraft deliveries into space means meagre order books for the launcher manufacturers. They increase their offering costs to make a profit, and the high cost of launches reinforces the cycle (in my terms, “launcher oppression”). At an average cost of US$25,000 per kilogram, any space program is seriously limited in what it can achieve. Reusability and cheap heavy-lifting eliminates this bottleneck and clears the way for a truly worthy space program. How come?

In Chapter 3 we briefly outlined the main steps required to establish an off-world mining facility. This begins with an exploratory phase that calls for comprehensive mineral prospecting to identify the spatial distribution of resource(s) of interest. As highlighted in Chapter 2, our knowledge of lunar and asteroidal resources is still only cursory. Mostly it is based on spectroscopic, photometric, radar, and interferometric analysis from orbit or using Earth-based apparatus.[7] The few hundred kilograms of samples retrieved by the Apollo crews are certainly not sufficient to accurately chart the distribution and concentration of lunar resources.

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[7] Spectroscopy analyzes the light that is reflected off the surface of a body to infer its composition; photometry can determine the rotation rate and shape of a celestial body; and radar and interferometry can measure its mass and size.

And we have only a few grams of asteroidal material obtained by a single probe![8] A prerequisite to a worthy space program is an intimate understanding of resource offerings and concentrations; grain size distribution and abrasiveness; depth of loosely compacted regolith; mechanical properties such as shear strength, hardness, compressive strength, friction angle, and elastic moduli; surface topography; geochemical and geophysical properties such as resistivity, gravity, and porosity; and seismic and electromagnetic surveys to help to scrutinize the interior of the target. The list could go on.

Within their capacious fairings the reusable and reasonably priced heavy lifters of SpaceX and Blue Origin could send swarms of automated orbiters and rovers to increase our knowledge of the resource offerings of the Moon and asteroids. We also need constellations of telescopes to survey for Near-Earth Asteroids and to map the asteroid belt. We urgently need to understand what resources are available. And this has to be undertaken in a consistent and expeditious manner. We can no longer wait years to dispatch a tiny probe to collect a whiff of powder! This will require factories to turn out such spacecraft in large numbers. Mass production is perhaps a term that is better suited to consumer products than space hardware, but surely it is not beyond our capabilities.[9] Apart from lowering production costs, it promotes faster hardware evolution and improvements in know-how. Nowadays there is monthly progress in information technology, electronic consumer devices, and automotive products. We can no longer afford the decade-long development cycles imposed by the “launcher oppression”. With the right infrastructure, if a spacecraft fails irremediably while in transit to its destination or part-way through its mission, a replacement can be rapidly built that exploits the lessons learned from the failure of its unlucky sibling. In this way, product improvement can progress at a rapid pace. In the process, development and manufacturing costs are driven down. This is because we are edging towards a condition akin to mass production. The next natural step is to create fleets of vehicles for specialized tasks. For instance, we could have a rover type for core sampling in the lunar highlands and another for sampling only M-type asteroids (rich in metals). One type of craft could be equipped solely for assaying by spectroscopy but inspect many asteroids.

One result of such an extensive prospecting campaign will be the selection of the first lunar sites and asteroidal bodies worthy of exploitation. There is a great deal of literature on the selection of an accessible lunar site capable of satisfying research or mining requirements, or both. At least in the beginning, mining should

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[8] This was done by the Japanese robotic spacecraft Hayabusa, which in November 2005 returned a collection of tiny grains from the Itokawa asteroid. Hopefully, other missions will have returned more specimens from other asteroids by the time you read this book.

[9] Just look at the way that SpaceX is mass producing Starlink satellites for an internet-in-the sky, launching them sixty at a time.

be conducted in an area whose topography presents as few hurdles as possible. A lunar mining site will surely require landing and launching pads for the delivery of mining equipment, habitats, spare parts, supplies, and so on, as well to ship the extracted resource to the factory that will process it – most likely in Earth orbit but possibly elsewhere on the Moon. A reasonably level surface with relatively few craters and boulders would be welcome. This would simplify surface mining using an apparatus such as the bucket slusher of Chapter 3, and accommodate processing plant machinery and habitats for humans. Other issues would be topographic features likely to minimize difficulties in excavation and greatly assist the feeding of raw material to processing equipment, while seeking to exploit one-sixth gravity. Surface topography would also affect the type of communications network required to govern the robotic machinery working in the field. The possibility of a lunar equivalent of a GPS-type satellite constellation is appealing but might not be available at the start. It might be necessary to start with a single antenna mast to command the operations of all of the robotic equipment, but repeaters would have to be added when the site expands because the horizon is closer on the Moon than it is on Earth. Any mountain ridges, crater rims, and peaks might severely limit the line of sight, so it would be best to select an area whose topography maximizes reception using the least number of antenna masts.

At least initially, it would make sense to select a site that can afford access to the greatest possible assortment of resources, such as aluminum, silicon, titanium, iron, oxygen and hydrogen. The boundary between a mare and the highlands would satisfy this requirement. Figure 7.2 shows a plausible lunar mining and beneficiation plant in such an area. The mining site has been split into two open-pit areas in order to access both types of terrain. A transportable conveyor belt in each pit receives raw material extracted by a bucketwheel excavator (or any other excavator system) and then feeds a permanent conveyor that delivers it to the beneficiation plant. The mining sites can also be placed underground, and a mix of surface and subsurface mining might well be pursued.

At this point, we should ask ourselves which destination we should tackle first. Should we focus on the Moon, the NEAs, or the asteroid belt? The answer depends on a variety of factors. Surely the available and desired resource(s) will be a powerful driver in deciding where to go. Then there is the cost in propellant to reach any given destination and return with a viable payload. When it comes to spaceflight, distances between destinations are not as significant as the propellant needed to travel between two points. In fact, remember that space travel is subject to the law of gravity and that to move from one celestial body to another it is necessary to counter their gravitational fields. The only way to do so is by acceleration, by changing the kinetic energy of the spacecraft.[10] The stronger the

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[10] This change is indicated with the symbol ΔV or with the lettering delta-V and is pronounced as delta-vee.

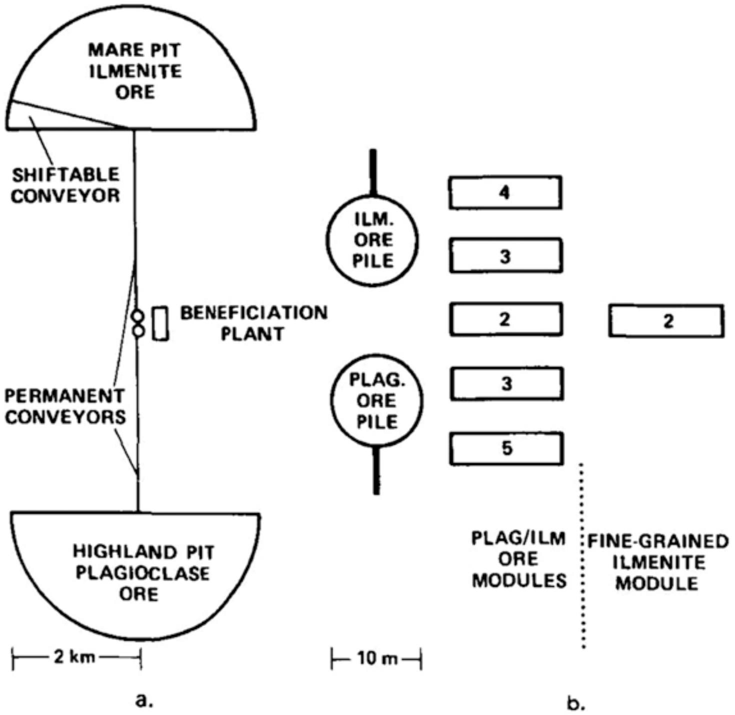

Figure 7.2 Schematic maps for a lunar mining (a), and beneficiation sites (b) at the border between a highland and a mare region.

gravitational field, the higher the necessary delta-V. The rocket equation $\Delta V = I_{sp} g_0 \ln(m_{initial}/m_{final})$ says how much delta-V a rocket engine can provide or, conversely, how much propellant must be budgeted for a required delta-V. The specific impulse (I_{sp}) measured in seconds, with higher values being better, defines the efficiency of a rocket engine in terms of thrust. For chemical propulsion, which is the one currently used by rocket launchers that employ two propellants subjected to an energetic exothermic reaction, it has a theoretical limit of 455 seconds. In fact, we have achieved this limit. The terms between the brackets represent respectively the mass of the vehicle at the time of igniting the engine to leave point A ($m_{initial}$) and the mass that remains at point B (m_{final}). The term g_0 is the gravitational acceleration relevant to the body.

Simply put, this equation says that to achieve the desired change in velocity there are only two terms that a rocket designer can work with. If we consider a constant mass ratio, the higher the specific impulse the higher the change in velocity. As we will soon see, alternative means of propulsion can deliver substantially higher specific impulses than chemical engines. Intervening on the mass ratio is not as simple as it might look. The difference between the initial and final mass is the propellant used in achieving a change in velocity. Once at the destination, the final mass has to include a meaningful payload. Because the mass ratio is a logarithmic function, the higher the delta-V, the higher the mass ratio must be until so much propellant must be carried that the payload (final mass) becomes zero.

To land on the Moon from an initial point in low Earth orbit (an altitude of 400 km, say), the total delta-V required is 6 km/s. This includes that for the outbound journey to a parking orbit around the Moon and that for the descent to its surface. To return to low Earth orbit, a delta-V of 3 km/s must be budgeted (the smaller value indicating the weaker gravity of the Moon). A total change in velocity of 9 km/s is thus necessary for a trip from Earth orbit to the lunar surface and back. By contrast, for many of the most accessible NEAs the total delta-V is 4.5–5.5 km/s. Although the Moon is much closer, its significant gravity field means it is a much more expensive target than an asteroid whose gravity field is negligible. This means that more propellant has to be burnt (and carried) for a landing on the Moon than on an asteroid, limiting the amount of payload. Furthermore, although in-situ production of propellant on the Moon could be achieved by extracting water from the regolith and electrolyzing it to oxygen and hydrogen, the amount of propellant burnt to lift off would once again be more significant than that to depart from an asteroid.

All things considered, therefore, it might be likely that exploration and exploitation of resources will occur on both the Moon and asteroids until experience and technology dictates which destination would best serve our purposes.

TRIAL AND ERROR AND THEN MORE TRIAL AND ERROR

It is highly likely that the road to a worthy space program will be characterized by a great deal of experimentation. This means that in parallel with the assessment of the resource offerings of the Moon and asteroids, a lot of effort must be devoted to trials of mining, processing, and manufacturing off-world until these techniques have been mastered to a sufficient level of confidence. In Chapters 3 and 4, we barely scratched the surface of what it would take to mine and process lunar and asteroidal resources. Likewise, in Chapters 5 and 6 we took only a fleeting glimpse at the intricacies and possibilities offered by low-gravity manufacturing. The technical literature is replete with in-depth reports and studies on how to recover this or that resource, or how to manufacture a specific product in zero-g. But apart from a number of investigations conducted initially on the Space Shuttle and then on the International Space Station, most of this remains hypothetical. It is time to put theory into practice, to understand what works and how it can be improved, or contrariwise, what is not viable.

There is really no limit to the amount of apparatus to be built and dispatched to the Moon in order to test and hone a given process for the purpose of extracting and processing a specific resource. As asteroids are surveyed, flotillas of APIS-like and RAP-like spacecraft should be directed to the most accessible targets to work out the bugs of those technologies. A parallel effort would occur in orbit, where low-gravity manufacturing is to be put through its paces until we are able to build manufacturing machines such as those described in Chapter 6. With so many processes, techniques and working methodologies to be investigated, there will be no shortage of questions requiring answers.

The International Space Station would be an ideal starting point. We could add modules to experiment with in-space manufacturing techniques, or indeed repurpose the entire outpost for in-space manufacturing rather than its role today of conducting research into pure science. The ISS is an infrastructure capable of generating a great deal of electricity. The originally planned facilities were scaled back to match budget limits so there is scope for expansion. Eventually, new space stations will be needed. Whereas the ISS was built as a generic-type of station to accommodate a variety of research activities, future space stations are likely to be smaller and specialized for the development of specific space manufacturing processes. Some might also sport a rotating section for simulated gravity, and trials should seek to understand if there are processes that would be better undertaken in a specific gravity field. In addition, a station with a variable gravitational field could reproduce the gravity of a target, to test apparatus that is intended to operate in that environment. This could identify and overcome weaknesses prior to sending the apparatus to its final destination.

This may sound like a lot of hardware to put up there, as indeed it will be, but let us not forget that we will have the reusable heavy lifting launchers of Blue Origin, SpaceX, and any other vendors who develop similar products. Hardware will be built on Earth and dispatched to the location for a fraction of the price currently demanded for expendable rockets. As time passes, ever more hardware will be orbited to enable an increasing number of investigations to take place either in space or on the surface of a celestial body.

As regards manufacturing in space, the first trials will surely adopt terrestrial raw materials. It would not be wise to wait for extraterrestrial resources to show up before starting to experiment with off-world manufacturing. Remember, the establishment of a worthy space program such as the one addressed in these pages requires a great deal of preparation, because our space programs so far have not been able to address the key issues that concern extraterrestrial mining and manufacturing. As off-world resources become available, manufacturing experimentation can continue with ever decreasing reliance on terrestrial resources.

We could even have space stations with their own asteroid that are dedicated to extracting their specific resources, or conversely are specialized to mine a particular type of asteroid. Relocating an asteroid might sound preposterous but it is a concept that NASA seriously studied in response to the Obama administration's request that astronauts visit an asteroid by 2025. The options were either to launch a crew in an Orion spacecraft to intercept a Near-Earth Asteroid and perform science for 30 days prior to returning home, or to bring the asteroid closer to Earth to make it accessible to multiple missions that would inspect, sample, and ultimately dismantle it to assess its internal structure and potential resource offerings. Based on an extensive study undertaken by the Keck Institute for Space Studies, a joint institute of the California Institute of Technology and the NASA Jet Propulsion Laboratory, NASA opted for the second alternative. Called the Asteroid Retrieval Mission (ARM) it would consist of a robotic spacecraft capable of grabbing a small asteroid or boulder off the surface of a much larger body, up to a mass of 1,000 tons. Propelled by a 40 kW Hall thruster fed by two large solar arrays generating up to 50 kW of electric power, the spacecraft would position the asteroid in a so-called distant retrograde orbit of the Earth-Moon system at an altitude of 70,000 km above the lunar surface. Although considerable progress was made in the development and testing of key technologies required for the retrieval spacecraft, on December 11, 2017, a Trump administration space policy directive commanded NASA to cancel the asteroid retrieval mission and concentrate on a return to the Moon. This was a shame, because asteroid retrieval is precisely the kind of cornerstone capability required for the roadmap advocated here.

APIS and RAP spacecraft are a suitable replacement for the ARM because both have the potential to move asteroids closer to Earth for deep mining and processing. In fact, depending on the consistency of the asteroid and its composition, additional apparatus might be required that would be best retained near Earth, where it can be employed continuously rather than being dispatched on a multi-year journey across the Solar System. It will be a matter of making trade-offs, and mission analysis and experience will dictate which option is best in each case. Most likely, there will be a combination of in-situ mining and relocation to a convenient spot in the Earth-Moon system.

Remember that we are aiming to establish a space-based manufacturing industry that can satisfy terrestrial needs by exploiting the resources extracted in space; hence the adjective “space-based”. We need to achieve as much autonomy as possible from resources imported from Earth. While at the outset experiments and the development of in-space manufacturing apparatus will depend on raw materials from Earth, in the long run we must break that link to reduce, if not actually eliminate, polluting mining activities on Earth. One way to achieve this goal will be to direct the initial in-space manufacturing activities to experiment with methods of self-replication.

Self-replication requires an orbital factory to be able to produce the components it requires for its maintenance, servicing, expansion, and reproduction. This includes pressurized modules, tankage, pipelines, solar arrays, radiators, structural elements, electronics, computers, and so on. It involves manufacturing the scouting spacecraft to survey sites for mining on the Moon and asteroids, as well as apparatus for mining and vehicles for deep space. If an orbital manufacturing plant can make flotillas of APIS and RAP spacecraft, or of mining spacecraft specialized for specific tasks, then it will be possible to gradually dispense with launching survey and mining spacecraft from Earth. The result will be a boost to the appraisal of resource, mining, and return of raw materials.

The early years of in-space manufacturing could be spent building interplanetary probes, science satellites, and space-based telescopes. For every scientific mission that receives funding now, several rival proposals have to be abandoned even though they were capable of delivering a great deal of scientific knowledge. In the future we could dispatch interplanetary probes to each major moon of the giant planets of the Solar System or build multiple Hubble-like telescopes to allow a greater number of astronomers to carry out observations. Spacecraft for removing orbital debris would be another practical demonstration for space-based manufacturing. This is a timely issue, as the pollution of orbital space with debris leftover by thousands of satellites and rockets has been receiving a great deal of attention. Kessler Syndrome scenarios are routinely played out.[11] Although we are still far from triggering such as an event, we would do well to develop a capability for removing sizeable pieces of space junk before they can endanger a fully functional space asset. Of equal significance is the need for an orbital servicing capability to refurbish and upgrade satellites in order to extend their operational lives. Orbital debris removal and servicing are often linked because they share technologies and modes of operation. The reason neither activity is currently being pursued arises from the lofty cost of launching a spacecraft just to refuel a sibling, or to dispose of it by atmospheric re-entry. When such vehicles are built directly in space, possibly using extraterrestrial resources, orbital servicing will become viable.

The first products of a fledgling space-based manufacturing industry will prove that it can be entrusted with the production of functional, utilitarian products for use on Earth.

In fact, as spacecraft are complex products, once one or more manufacturing and assembly lines have been established, this in itself will provide ample evidence that in-space manufacturing and assembly can attain the same standards as on Earth. This will clear the way for in-space production aimed at terrestrial markets, but we should proceed in steps. The first spacecraft or space hardware might be simple and include components made on Earth. These might be proofs-of-concept designed to hone in-space manufacturing and assembling skills. Inevitably, an ever increasing number of components will be produced in-situ from materials obtained in space.

By pairing the inflatable technology discussed in Chapter 6 with the heavy lifting capacity of a Starship or New Glenn rocket, we will be capable of establishing

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[11] The Kessler Syndrome proposed by NASA scientist Donald J. Kessler in 1978 is a scenario in which the density of objects in low Earth orbit is high enough that collisions between objects could cause a cascade in which each collision generates space debris that increases the likelihood of further collisions.

in an expeditious manner small and large space stations for manufacturing research. One such facility could be fashioned in the style of the microchip manufacturing plant in Chapter 6 and offer the possibility of starting the manufacturing of high-technology products needed for the kind of spacecraft production lines discussed above. As with all new ventures, experimentation and trials will provide the knowledge to determine what works best for particular activities.

PROPULSION

Space travel is not really as it is depicted in science-fiction movies and novels. Apart from rockets used to launch a payload into orbit, spaceflight is painfully slow. Even reaching Mars from Earth requires 6-8 months at best, when the two planets are at their closest range. The superb images of Saturn beamed by the now defunct Cassini mission began to arrive after a 7-year-long journey through the Solar System. If you remember the rocket equation, you can readily understand the problem. The equation has two main terms, the specific impulse and the mass ratio. The higher the specific impulse and the mass ratio the greater is the delta-V, or in other words the faster we can travel. However, carrying large quantities of propellant for considerable delta-V is impractical because there comes a point where the propellant is just barely able to push itself around, let alone a useful payload.

This is why the APIS and RAP architectures envisage processing local resources into the propellants required for the journey home. This is a good solution, but again, depending on the orbit of the mined asteroid, it might be years before their resources are accessible for manufacturing in a space-based industrial plant. Ideally, we would like to operate the rocket engine continuously to provide a constant acceleration, as is often depicted in science-fiction productions. This would shorten a trip of years to months or even several weeks. However, doing so with present-day chemical rocket technology would require a high rate of propellant consumption and therefore a vast amount of propellant. But the sheer amount of propellant would reduce the available acceleration to the point of making constant-acceleration travel impractical. Hence, interplanetary missions are characterized by short bursts of high thrust followed by excruciatingly long coasting periods with the engine off, traveling at a constant speed along an elliptical path known as a Hohmann transfer.[12]

Along with faster travel times, we also want to haul sizeable payloads. So far the heaviest spacecraft dispatched on an interplanetary mission was Cassini, with a mass at launch of 5,712 kg. If we are serious about exploiting space resources,

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[12] One trick to increase the speed of an interplanetary probe without firing its engines, is to swing by a planet to capture kinetic energy. It is the equivalent of playing pool, where the direction and speed of a ball can be changed by planning the interaction between two balls. Applied to interplanetary travel, this strategy is referred to as a fly-by or gravitational assist. It is usually performed multiple times and can enable missions to reach targets anywhere in the Solar System.

then we must be able to reach a destination in a reasonable time and, if necessary, with heavy and cumbersome mining equipment for resource recovery. It might actually be better to perform materials processing in-situ, so that only processed raw material need be returned to near-Earth space.

Increasing the specific impulse is a possibility, but we have already hinted at how chemical propulsion is close to its theoretical limit. The most powerful combination of such propellants (hydrogen and oxygen) yields a specific impulse of no more than 450 seconds.[13]

Improving the specific impulse would achieve substantial savings in propellant. For instance, by appropriate development of the rocket equation we find that for the same delta-V, a doubling of the specific impulse of a chemical rocket would reduce the propellant requirement by a factor of 2.2. This would make constant acceleration a viable proposition. To understand how we can achieve such a dramatic result, recall that the specific impulse is a function of the temperature of the burnt gases and their mean molecular weight. In particular, the higher the temperature and the lower the molecular weight, the greater the specific impulse. This is reasonable, because higher temperatures reflect higher kinetic energy. Hence the faster the burnt gases flow out of a rocket nozzle, the greater the thrust produced. Furthermore, the lower the molecular weight, the easier is to accelerate the individual molecules or atoms of the burnt gases to a higher velocity for increased thrust.

An alternative to chemical rocketry that can achieve a higher specific impulse is the nuclear thermal rocket (NTR). Several configurations have been proposed over the decades but the principle remains the same. Instead of a combustion chamber,[14] there is a nuclear reactor core. The fission of uranium generates heat that is collected by a working fluid. In passing through the core, the fluid is superheated and expands into a nozzle to generate thrust. Hydrogen is the propellant of choice for having the lowest molecular weight. It can achieve a specific impulse of 900 seconds. The upper limit is the amount of heat that the reactor can generate without structural damage as a result of melting. Higher specific impulses could be attained with nuclear reactors that use a gaseous instead of a solid core. As of today, experimentation with nuclear-based rocket engines has been with solid cores like those used in commercial nuclear power plants.

In a variant known as Nuclear Electric Propulsion (NEP) the nuclear reactor acts only as a source of thermal power. The heat is converted into electricity to power an electric propulsion system that accelerates an ionized gas or plasma through electric and magnetic fields. Depending on the configuration of the engine,

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[13] Slightly higher specific impulses could be achieved using fluorine or beryllium, but these are too toxic and expensive to deal with. Considering that they would increase the performance of a rocket engine only slightly, the hydrogen/oxygen combination is the best that chemical propulsion has to offer.

[14] In a chemical rocket, the combustion chamber is that portion of the engine where the propellants undergo a chemical reaction that develops gas at high pressure and temperature. This is then directed to the nozzle to produce thrust. Combustion chambers are usually cylindrical in shape.

specific impulses of the order of several thousands of seconds can be achieved. However, their thrust is so low that these engines cannot launch from a planetary surface, they are suitable only for use in space. On the other hand their ability to operate continuously for long periods, years even, means they can be used for interplanetary flights.

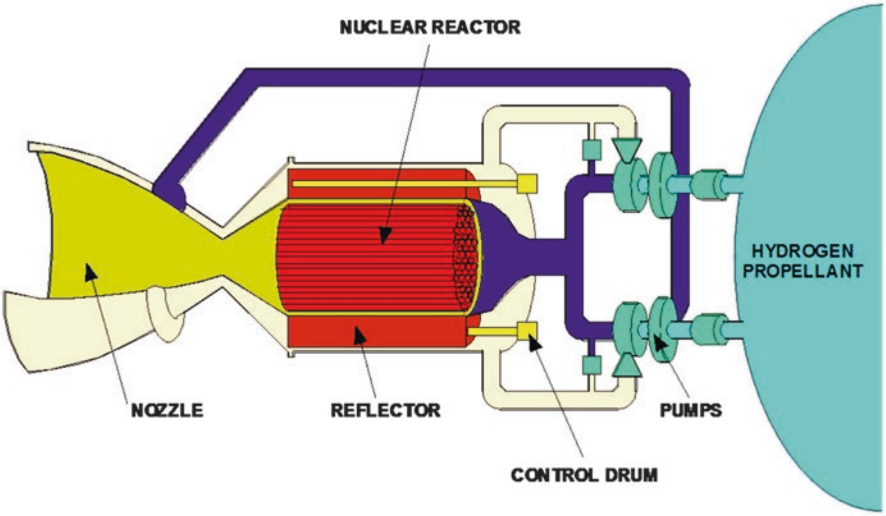

Figure 7.3 The major elements of a nuclear thermal rocket.

Of the various electric propulsion systems which could be powered by a nuclear reactor, the Variable Specific Impulse Magnetoplasma Rocket (VASIMIR) exploits the best of two worlds. Invented by seven-flight Space Shuttle astronaut Dr. Franklin Chang Diaz, it functions by injecting a gas such as argon, xenon, or hydrogen into a tube that is surrounded by magnets and radio wave couplers. The gas is first ionized by helically shaped radio waves emitted by a so-called helicon coupler. The resulting plasma attains a temperature of 6,000 K.[15] Because it consists of charged particles it can be confined and manipulated with a magnetic field. A second coupler, called the ion cyclotron heating system, increases the temperature of the plasma to 10 million degrees. The energy of the plasma is then converted into an axial motion so that it can be expelled from a magnetic nozzle. There are several advantages to this system. Firstly, it can process a large amount of power, such as that from a nuclear reactor, to produce a high thrust and hence specific impulse. By keeping the power constant this engine can vary the thrust and specific impulse depending on the mission phase. While traveling between two destinations in space, the engine can yield a constant and moderate thrust for a useful acceleration and a high specific impulse. When the vehicle has to slow down at its destination

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[15] This is comparable to the temperature of the solar photosphere.

the thrust can be increased to reduce the capture time at the expense of the specific impulse. The system is suitable for moving heavy payloads around in low Earth orbit, as well as between objects in deep space such as the Moon and asteroids. By permitting constant acceleration this engine will considerably shorten travel times.

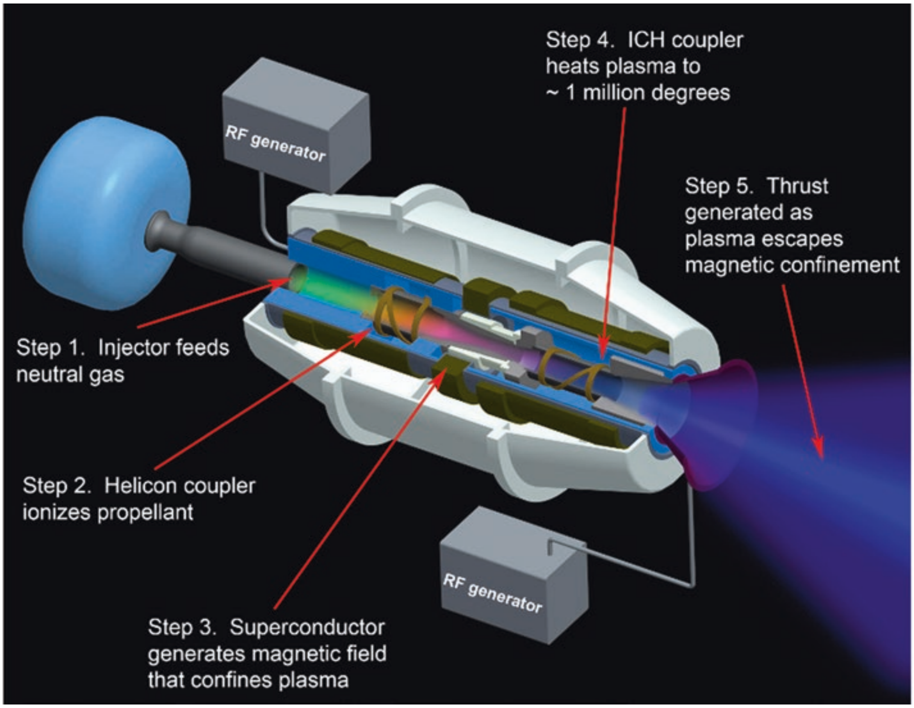

Figure 7.4 The main components of VASIMIR (Copyright Ad Astra Rocket Company © all rights reserved).

Dr. Chang and his team at the Ad Astra Rocket Company have been working on the VASIMIR design for four decades. It is possible that a prototype will be installed on the International Space Station. By drawing electric power from the solar panels it will demonstrate the concept. By using waste hydrogen produced onboard, it might even undertake the routine of counteracting the ever-present atmospheric drag. This would reduce the amount of propellant ferried up from Earth to enable conventional engines to periodically boost the station's orbit.

ENERGY

The role for nuclear in space is not restricted to propulsion. As noted, the reactor for Nuclear Electric Propulsion powers an electric engine rather than produce thrust. A nuclear plant is ideal for powering a space station, spacecraft, or an industrial facility on the surface of a celestial body. The solar panels of space stations in Earth orbit recharge chemical batteries to supply power when the outpost is in darkness, which is approximately half of an orbit at low altitude. If we are to build very large space infrastructures for manufacturing activities in space we will need a plentiful supply of energy, so much so that solar power might become impracticable from a structural and attitude management point of view. A mining facility on the Moon that is not in a polar region has a fortnight of light and a fortnight of darkness. If it relies on solar power then the energy-hungry apparatus would be inoperable for half the time. That would be an absurd situation. Nuclear is the only compact source of such enormous amounts of power.

In recent years the concept of deploying Small Modular Reactors (SMR) has been investigated as a way of developing safer and more affordable nuclear power plants. One, HolosGen LLC in Virginia, specializes in the development of mobile, scalable, integral nuclear generators. Its HOLOS product is a compact nuclear reactor capable of delivering up to 13 MW for 20 years. The reactor heavily exploits off-the-shelf turbo-machinery components made for the aviation industry, direct-drive generators made for renewable energy sources such as wind-powered systems, and waste heat recovery systems made for high-power electric motors such as hybrid autos. All of the hardware is housed inside a sealed shipping container. Four independent power modules produce energy. Each is a closed-loop version of a jet engine in which there is an assembly of sealed subcritical nuclear fuel cartridges instead of the combustion chamber. The working fluid is helium or carbon dioxide because their higher energy carrying-capability is greater than air. The power module works like a conventional jet engine in that the working fluid is first compressed and then delivered to the fuel cartridges where it heats up and expands into a turbine connected to the compressor (so that it can keep compressing the working fluid) and to a generator for electricity. After the turbine, the fluid is directed to a heat exchanger where it cools down prior to being fed to the compressor. In a conventional jet engine the air is expelled from a nozzle to produce thrust. Here the fluid is recycled into the compressor. The reactor is inherently safe because it can work only when the four power modules, which are in independent steel pressure vessels, are coupled together, because it is in that state that the nuclear fuel achieves the criticality necessary to sustain a chain reaction and produce heat to drive the turbines. The position of the power modules is governed by an active automated system called the Automatic Module Positioning System that is based on fast actuators similar to those of aircraft flight-control system actuators. The HOLOS generators can be clustered to satisfy different power demands and the technology is scalable. For instance, a version capable of delivering up to 81 MW is composed of four larger subcritical power modules, each housed within the volume of a container. Given its modest size and ability work as a stand-alone power plant, a HOLOS reactor could serve a variety of roles ranging from military bases to areas affected by a natural disaster or areas lacking a power grid infrastructure.

Although HOLOS is not advertised for space applications, it is easy to envisage this technology being adapted to power either a space station or mining facilities on the Moon and asteroids. Such a reactor would be suitable for applications where the health of workers is of paramount importance because the fuel is hermetically sealed into a container whose structure is reinforced by multiple shields. This safety feature would help to overcome the longstanding antipathy of the general public to sending nuclear material into space.

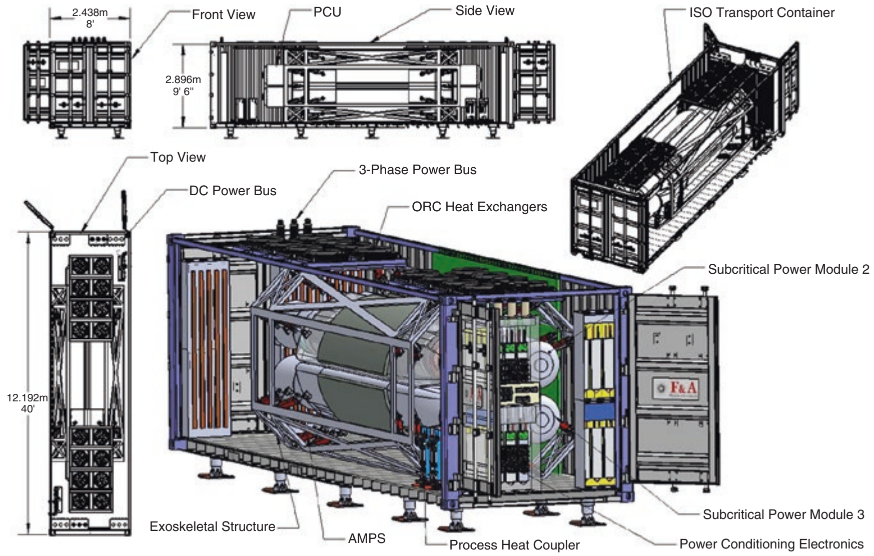

Figure 7.5 The main components of the HOLOS reactor.

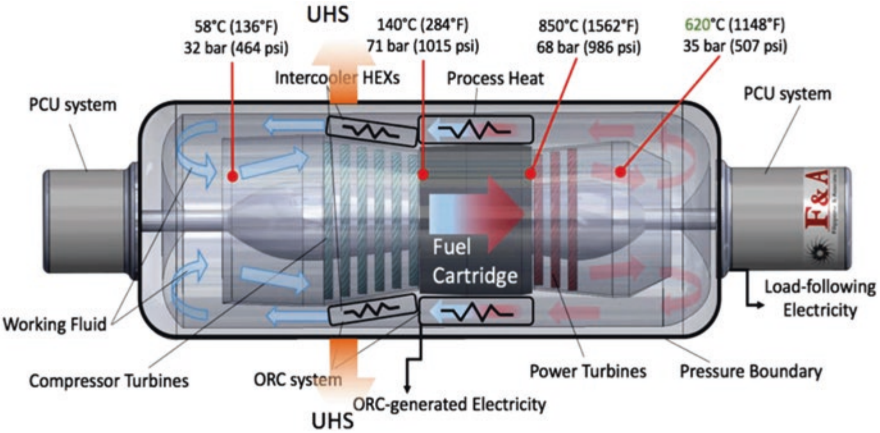

Figure 7.6 The closed-loop cycle of the HOLOS power module.

In 2015 NASA partnered with the Department of Energy and the Los Alamos National Laboratory for the Kilopower project. This is seeking to develop a compact reactor capable of producing from 1-10 kilowatts continuously for at least 10 years. At present, the 1 kW version weighs 400 kg and the 10 kW version weighs 1,500 kg. It uses a solid cast uranium reactor core whose heat is transferred via passive sodium heat pipes to a high-efficiency Stirling engine which employs that heat to pressurize a working fluid to move a piston coupled to an alternator and thus produce electricity. This is not dissimilar to the operation of an auto engine. The reactor possesses high design margins for life and reliability, high redundancy for fault tolerance, graceful degradation, and features to prevent inadvertent criticality of the fuel and run-away temperatures. It is designed to be launched into space cold, then turned on and off as needed. Like the HOLOS reactor, Kilopower is a modular design to enable multiple units to be coupled to satisfy a variety of energy needs. NASA is testing a full-scale prototype named KRUSTY (Kilopower Reactor Using Stirling Technology) at the Nevada National Security Site. The results to date are promising. Such reactors could power missions in deep space, particularly settlements on the Moon and Mars.

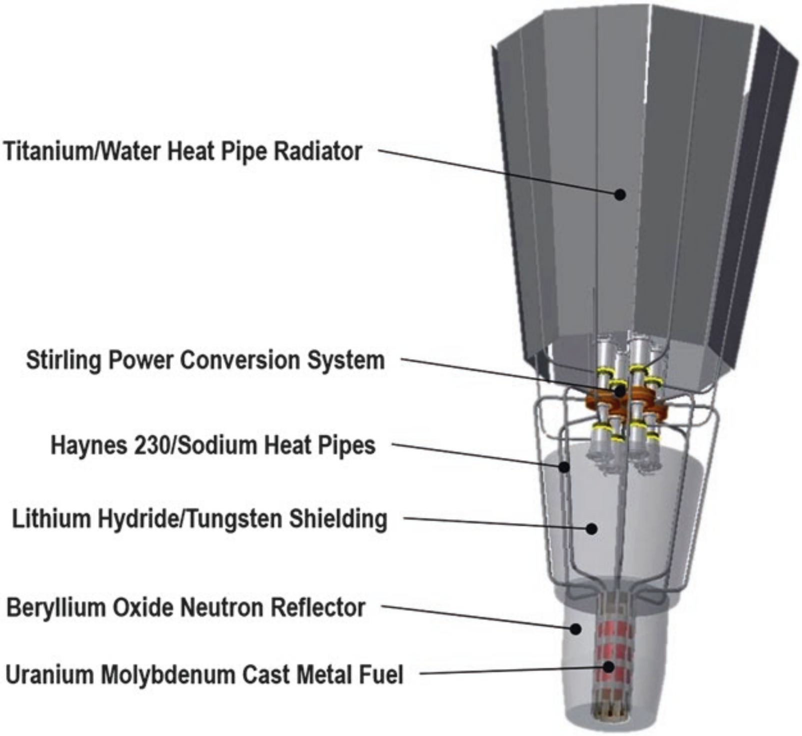

Figure 7.7 A cutaway view showing the configuration and main components of the Kilopower apparatus.

LAWYERS IN SPACE

Any respectable discussion concerning the recovery of space resources cannot omit the legal constraints. These are defined by the 'Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies', more popularly called the 'Outer Space Treaty' (OST). It came into force on 10 October 1967. As of June 2019, 109 countries are parties to the treaty and another 23 have signed it without completing the ratification process. The twenty-seven articles of the OST provide an international legal framework for the conduction, management, and supervision of space exploration-related activities, and in particular the utilization of space and its resources. For instance, the very first article asserts that "the exploration and use of outer space … shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind." It continues, "Outer space … shall be free for exploration and use by all States without discrimination of any kind … and there shall be free access to all areas of celestial bodies."

With the prospect of mining resources in space approaching reality, the existence of the OST has prompted considerable debate. At issue is the vague language of the Treaty, which reflects the historical context in which it was formulated. At the dawn of the Space Age, both the Cold War superpowers recognized the need to prevent an escalation of their animosity into space. This is why Article IV explicitly bans State Parties from placing nuclear weapons or any other weapons of mass destruction into orbit or on celestial bodies, and requires exploration to be exclusively for peaceful purposes. However, the OST was also a compromise between two radically different political and economic ideologies: the private enterprise-driven capitalistic approach versus the state-controlled Communist model. While the United States wanted space development opened to private commercial entities in partnership with governmental programs, the Soviet Union said only States should be in charge of and responsible for activities in space. A compromise was reached with Article II, which deals with issues concerning the ownership of a celestial body or its resources: "Outer space … is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." Although this is the shortest article in the OST, it is hotly contested by two schools of thought, one of which says that the OST does not banish private entities from removing resources from a celestial body and utilize them and the other insisting it forbids all forms of appropriation, national or private.

The argument centers on the definition of "sovereignty", a nation's right to exert exclusive authority over people, resources, and institutions within the boundaries of its territory. This is referred to as "absolute territorial sovereignty". But governments can also exert their sovereignty outside national borders. This is called "functional sovereignty". It is limited to certain specific functions such as jurisdiction over ships, aircraft, and citizens abroad. While functional sovereignty isn't explicitly mentioned in Article II, Article VI hints at it: "State Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities. … The activities of non-governmental entities in outer space … shall require authorization and continuing supervision by the appropriate State Party of the Treaty."

Article VIII undeniably accounts for it: "A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body." Hence, a spacecraft or habitat on the surface of a celestial body is under the jurisdiction of the State of registry, but only so far as the activities carried out by that infrastructure and its occupants are concerned.

If Article VIII accepts a nation's functional sovereignty, it follows that Article II only prohibits absolute sovereignty. Hence, a State Party cannot declare ownership by a land claim. Private appropriation and therefore property right ownership, which would allow for the extraction and utilization of resources, are not precluded because they are not explicitly alluded to. This interpretation is congruent with the *expressio unius est exclusio alterious* legal doctrine whereby the explicit mention of one thing is the exclusion of another. It follows that when interpreting statutes, whatever is not explicitly mentioned is presumed to have been because it was left aside by deliberate choice rather than unintentionally.

This was reinforced by the ratification in 1979 of the 'Agreement Governing the Activities of States on the Moon and Other Celestial Bodies', better known as the 'Moon Treaty' or 'Moon Agreement'. Its intention was to clarify aspects of the OST and establish a regime for the use of the Moon and other celestial bodies. Article 11 declares: "Neither the surface nor the subsurface of the Moon, nor any part thereof or natural resources in place, shall become property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person. The placement of personnel, space vehicles, equipment, facilities, stations and installations on or below the surface of the Moon, including structures connected with its surface or subsurface, shall not create a right of ownership over the surface or the subsurface of the Moon or any area thereof." Despite its name, the Moon Treaty explicitly states, "The provisions of this Agreement … shall also apply to other celestial bodies within the solar system, other that the Earth." The absolute prohibition of private property rights is a sign that the authors of the Moon Treaty did not feel that the OST had imposed such a ban. It is worth noting that although the OST has been signed by more than 100 countries, including all those nations that possess an indigenous launch capability, as of writing this book in 2019 the Moon Treaty had been signed only by 18 nations, none of them spacefaring. Presumably, the spacefaring nations did not appreciate an outright ban on private property rights. While the OST is now considered customary international law, making it applicable also to non-State Parties to the Treaty, the Moon Treaty is regarded in legal terms as dead letter and thus its provisions are not taken into notice. It follows therefore, that the OST *does* enable a country to recognize private property rights to space resources. Another argument in favor of such an interpretation is the fact that, as previously noted, neither the United States nor the Soviet Union wanted to yield their ideological stance and the vague language of the OST represented an acceptable compromise. The private commercial enterprise-driven USA could never have accepted an explicit ban on private property rights.

The question is far from being closed, however, as subscribers to the no-private-property-rights school continue to make their voices heard. Perhaps, it is time for the Outer Space Treaty to be updated with more precise and explicit language designed to remove any ambiguity and bestow upon private commercial companies the legal authority to conduct space resource mining and other forms of business in space. On the other hand, when it was written, the exploration of space was just at its beginning and countries had more pressing issues than to provide an explicit approval for what future private entities could and could not do in space. As we have seen, what was important to the leading signatories of the Treaty was to ensure that space would not become a new battleground. The rationale for space, like that for Antarctica, was to reserve it for peaceful uses only.

One step in the right direction occurred in 2015 when the US Congress passed the Commercial Space Launch Competitiveness Act, also known as the Spurring Private Aerospace Competitiveness and Entrepreneurship Act, or given its acronym, the SPACE Act. Among other things, this contained a paragraph on asteroid resource and space resource rights: “A United State citizen engaged in commercial recovery of an asteroid resource or a space resource … shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid resource or space resource obtained.” To avoid any infringement of the OST, it included a disclaimer on extraterritorial sovereignty: “It is the sense of Congress that by the enactment of this Act, the United States does not thereby assert sovereignty or sovereign or exclusive rights or jurisdiction over, or the ownership of, any celestial body.”

In 2017 Luxemburg became the first European country to provide a similar legal framework. Article 1 of the Luxembourg Law on the Exploration and Use of Space Resources definitively states: “Space resources are capable of being appropriated.” Article 3 clarifies that authorization “shall be granted to an operator for a mission of exploration and use of space resources for commercial purposes” and Article 4 says “the authorization for a mission shall only be granted if the applicant is a public company limited by shares or a corporate partnership limited by shares or a private limited liability company of Luxembourg Law or a European Company having its registered office in Luxembourg."

Perhaps it would be helpful if other countries were to establish similar laws for themselves and encourage the negotiation of treaties for international cooperation as well as for the recognition of claims by entities that are based in any of the signatories of such agreements. This would significantly contribute to an orderly exploitation of space resources.

INTERNATIONAL COOPERATION

Putting legal aspects aside, another crucial dispute relates to who should be able to develop and establish a space program as outlined in this chapter. The United States and the European Union might be able to, even though space exploration is one of those fields that appear particularly well suited to international cooperation. Several distinctly complex scientific endeavors would never have passed beyond the concept stage if it had not been for an extensive pooling of international resources. One such case is the International Thermonuclear Experimental Reactor (ITER) being built in France. Nuclear fusion for electricity power generation has been under development for decades by scores of scientists worldwide who have openly shared their findings. It is one of the trickiest problems humankind has faced, because it involves creating and, more importantly, controlling what effectively is a miniature star. Scheduled to begin working no earlier than 2025, ITER will be the largest fusion research facility ever built. The goal is to achieve ignition of the nuclear reaction and sustain it. It will also be the testbed for the integration of technologies, materials, and physics regimes for future commercial production of fusion-based electricity. The ITER organization has seven members: China, the European Union, India, Japan, South Korea, Russia and the USA. Membership is not primarily a matter of providing financial backing, instead some 90% of participation is in the form of components, systems, buildings, hardware, software, documented data, methods of research and development, and so on. The members will share the intellectual properties which derive from the design, construction, and operation of ITER. For instance, if country 'A' is in charge of the design and manufacturing techniques of the superconductive coils that generate the magnetic field to confine the plasma, that intellectual property will be distributed to the entire organization so that all other members can learn how to manufacture such coils. Of course, those other members might find it more advantageous to order their coils directly from country 'A'. If so, members will be able to develop their industrial capabilities for the future commercial exploitation of the technologies that they have specialized in mastering.

Productively managing nuclear fusion is so tricky that no one country, regardless of its development status, could achieve it on its own. The only course of action is a collaboration at an international level where information on science and engineering is shared freely. As the ITER experiment continues, and the science and engineering are honed, any member can learn from the working of the ITER reactor and prepare its industrial infrastructure, scientists, and engineers for the implementation of their individual domestic commercial nuclear fusion power plants. ITER is not meant to become a commercial nuclear fusion reactor. It will enable the membership to learn how to overcome the problems and then build their own commercial nuclear fusion plants.

As stated throughout this book, space mining and space-based manufacturing will require addressing sufficient scientific, technical, and engineering issues to occupy armies of scientists and engineers for decades to come. A program of this complexity will justify international cooperation in an ITER-like fashion, characterized by open sharing of scientific and technological discoveries.

For the sake of argument, let us call this the International Organization for Space Development (IOSD). It could manage the assembly and operation of one or more large crewed orbital infrastructures to address basic science and engineering issues relating to space-based manufacturing of high-technology products and hardware for spacecraft. The organization could identify a number of asteroids and lunar sites as candidates for assessing and developing resource appraisal and mining. One or more outposts could be delivered to small asteroids for additional development of resource extraction and beneficiation techniques which might need human supervision. IOSD would be granted international legal recognition, including the capability to conclude agreements with States and international organizations.

As in the case of ITER, each member of IOSD will contribute primarily in terms of specific components, equipment, materials, goods and services, staff, and so on, and members will disseminate and exchange all published data, drawings, designs, computations, reports and other documents, methods of research and development, technical know-how and processes, technological solutions, and inventions that are developed by individual members and by the organization itself on an ongoing basis. Note that knowledge will be produced both by the individual members as they develop components for experimental research mining facilities on the Moon and asteroids and for orbiting manufacturing, and also by the organization itself. This knowledge would include an understanding of what works best and how to improve existing designs. No matter where, when, or how the information originates, it will be equally shared among the members. As with ITER, this sharing of information would be on an equal, non-discriminatory, non-exclusive, royalty-free basis so that each member is then able to develop their own domestic space-based industrial capability by contracting private industry, either their own or that belonging to other members. Most probably, as with ITER, members might specialize in the design and construction of a specific piece of equipment and thereby become the prime supplier to the other members. Such an approach would benefit each member, because they would have a guaranteed market and resultant economic returns.

Should such an organization be composed of state members or private industry? In the case of ITER, each member set up a so-called “domestic agency” which would manage all of its activities as a member of the organization and serve as the point of contact for industry. This template could be applied to IOSD. Individual states and political or economic unions would be eligible for membership. In turn, they would establish their domestic agency that we could label as a national space development agency, giving it the exclusive role of promoting activities that support the work and goals of IOSD and assuring openness of knowledge, ideas, results, and technology. In parallel, national space development agencies would encourage and oversee the development of an indigenous space development program which would best exploit the synergies of a public-private partnership. In other words, members would do well to incentivize the growth of a native commercial private industry, then make full use of it. The fact of the matter is that private companies can achieve better results more rapidly than their public governmental counterparts. For example, look at the money-wasting Space Launch System that the United States has been developing for the last decade. Meant to return NASA to the Moon, this heavy expendable launcher is years behind schedule and, even worse, many times over budget. In that same span of time, and for a tiny fraction of the cost, SpaceX has provided a reliable service of reusable rockets. At the time of writing this book, the company is only a few years away from introducing the Super Heavy and Starship combination. Once qualified, this vehicle will open an era of hauling prodigious amounts of payload into orbit. Will the Space Launch System be available by that time? Even if it is, it is projected to have a very low launch rate, perhaps only one per annum. It is certainly not being built to initiate and support a space infrastructure such as is advocated here. Private space companies hired by governmental institutions and targeted to further the development of space manufacturing would prove essential in assuring a more efficacious accomplishment of the IOSD mandate.

The national space development agencies would resemble the National Advisory Committee for Aeronautics (NACA) founded on March 3, 1915, as a federal agency to supervise and direct scientific investigations of the issues of flight, with a view to practical solutions. By NACA, the federal government created research facilities and financed research into the science of aerodynamics, propulsions, materials, and other disciplines of aeronautical engineering. Before it was incorporated into the National Aeronautics and Space Administration (NASA) in 1958, NACA produced a wealth of knowledge on every possible aspect of flight and made this openly available to all aircraft manufacturers. As a result, the American aero industry rapidly evolved from a cottage-like industry to one which was capable of mass-producing state-of-the-art civilian and military aircraft. Those decades produced a profusion of aircraft design concepts, as experiments were carried out to understand every possible aspect of the design and operation of aircraft.

An International Organization for Space Development and its associated national space development agencies should therefore be structured like NACA, and actively support experiments on any discipline related to the development of extraterrestrial mining and space-based manufacturing.

The NACA model also helps us to appreciate how the road to a worthy space program will never end, because even when a destination is reached, the territory to explore is limitless. Even when we have mastered the art of extraterrestrial mining, processing, and manufacturing, the required technologies will continuously evolve, improve, and become more efficient as new requirements and capabilities are made apparent.

FLIGHT OF FANCY OR REALITY?

A space program with such a multitude of elements will undoubtedly give rise to the usual objections against space exploration: namely that it is too difficult, too costly, too dangerous, and so on. But the human race has performed incredible achievements of engineering whose complexities rival the mining of faraway asteroids, or building large orbital infrastructures for manufacturing.

Take for instance the Berkut oil rig that was built for Sakhalin-1, an international consortium of oil companies from the United States, Russia, Japan and India. Its goal was to extract 4.5 million tons of hydrocarbons per annum in the harsh, space-like, subarctic climate of the Sea of Okhotsk on the Pacific Coast of Russia, just north of Japan. Its topside structure with the drilling rigs, processing facilities, living quarters and other ancillary facilities weighs 200,000 tons and rests on four gigantic concrete shafts that took 52,000 tons of concrete and 27,000 tons of steel to build. Both the topside and the concrete shaft support structures were built onshore, then carefully transported to the site and assembled using gigantic floating cranes. The platform is designed to accommodate waves 18 meters tall, the crushing pressure of floating ice 2 meters thick, temperatures of –44°C, and magnitude 9 earthquakes. Oil rigs tend to be open-air structures, but in the punishing subarctic climate heavy winter gear is necessary to work exposed to the elements. No one would want to work like that for hours on end, certainly not when performing a dangerous job that requires vigilance to avoid a deadly mistake. In this case, therefore, the entire platform, including the derrick for the drilling apparatus, is completely sealed from the harsh environment and powered continuously by four 60-MW gas turbines and three 5.4-MW auxiliary diesel generators, day in, day out. In effect, Berkut is like a spacecraft because it is completely independent and able to resist one of the most inhospitable environment on Earth.

Never has the mining industry been so resolved to conquer the most inhospitable and inaccessible environments to extract their riches. The easy and profitable mining field are rapidly reaching depletion and are no longer economically viable to exploit. One of the new environments is the deep seafloor and its potential source of metallic minerals, particularly high grade copper, gold, zinc and silver. These are drawn from the mantle by submarine volcanism, typically hydrothermal activity where enriched fluids emerge from chimney-like structures. Nautilus

Figure 7.8 The Berkut oil rig.

Minerals Inc., aims to become the first company to commercially explore the seafloor to extract such resources and it has been busy developing mining equipment adapted from the offshore oil and gas industry, as well as from the dredging and mining industries. Currently, the company has a mining lease for the so-called Solwara-1 deposit, located in the Bismarck Sea, which is in the territorial waters of the Independent State of Papua New Guinea. The equipment to be lowered to the seabed at a depth of 1,600 meters consists of three tools: the auxiliary cutter, the bulk cutter, and the collecting machine. The cutters are to disaggregate the rock material on a continuous basis, like some mining machines for coal or other bulk materials on land. The robotic collector will use internal pumps to direct the sand, gravel and silt into a flexible pipe that leads to the riser and lifting system. From there, the seawater slurry containing the fragmented rocks will be sent to the Production Support Vessel, a large ship with accommodations for 180 people. After dewatering, the recovered rocks will be temporarily stored in the ship's hull until offloaded to a second vessel that will visit every 5 to 7 days. In the meantime, the water separated from the rocks will be returned to the seafloor, minimizing the environmental impact of the mining operations by eliminating mixing with the water column above the seafloor.

As Nautilus Minerals is gearing up for their first deep sea water scouring project, another mining activity has been underway off the coast of Africa for several years. This time the product is not minerals for the manufacturing industry, but diamonds. Owned by the De Beers Corporation, the MV Mafuta (formerly known

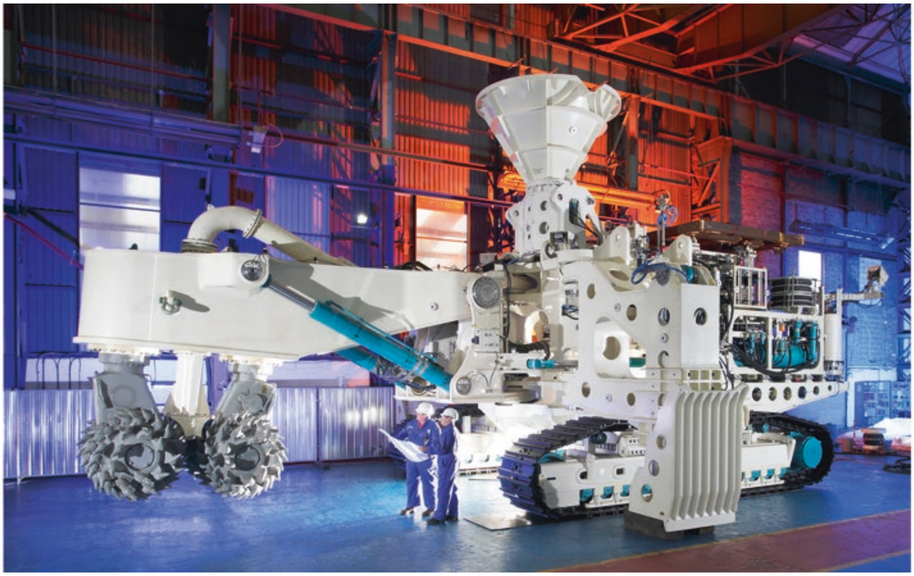

Figure 7.9 The Nautilus Minerals Auxiliary Cutter (used with permission from Nautilus Minerals, Inc.)

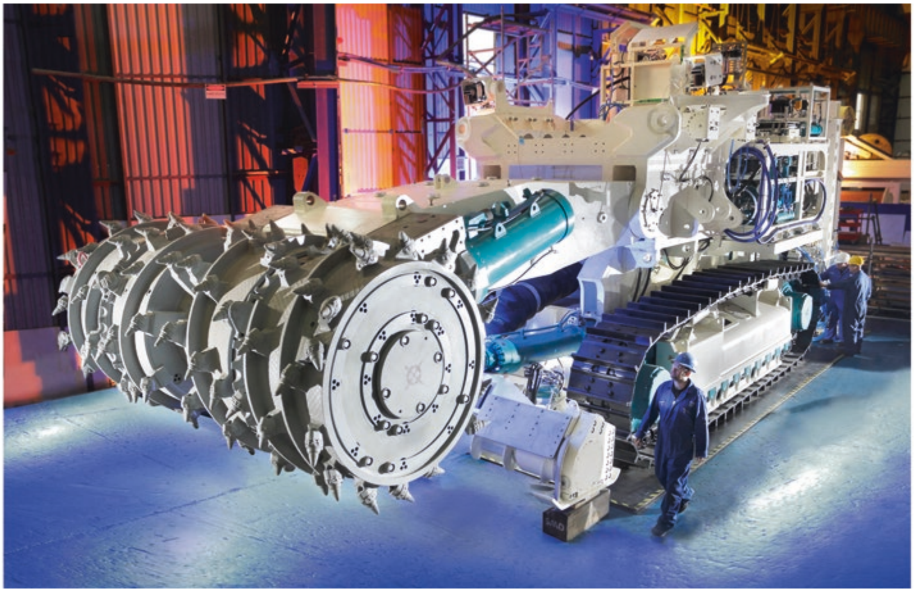

Figure 7.10 The Nautilus Minerals Bulk Cutter (used with permission from Nautilus Minerals, Inc.)

Figure 7.11 The Nautilus Minerals Collecting Machine (used with permission from Nautilus Minerals, Inc.)

as Peace of Africa) is a dredging vessel designed to scoop up the seabed material and sieve it for the shining carbon-based rocks that were transported there by rivers on the African continent. The vessel is equipped with a 240-ton remotely controlled seabed crawler that can be lowered to a depth of 150 meters and can dig trenches up to 12 meters in depth. The seabed material and water are pumped to the ship through a flexible hose 65 centimeters in diameter. On board, screening and sieving apparatus treats the raw material until only a diamond-rich residue is left. This is airlifted ashore weekly for further processing. The seawater and unwanted material is returned to the seabed. In addition to the dredging crawler, the ship also employs an autonomous underwater vehicle to make a 3D image of the diamond trails for the crawler to mine. It will also monitor the seabed to assess the impact of the operations on the marine environment.

If extracting diamonds from the seabed does not appeal much to you, what about a clandestine recovery of an enemy submarine? Enter the Glomar Explorer, a vessel built in the early 1970s by eccentric tycoon Howard Hughes for his company Global Marine Development Inc., to collect manganese nodules from the ocean floor.[16] In fact, the ship was built for the Central Intelligence Agency to

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[16] Also known as polymetallic nodules, these are ovoid or spherical rocks comprising concentric layers of iron and manganese hydroxides that formed around a core. They are of economic interest because they contain valuable metals and because there are vast numbers of them on the ocean floors.

secretly hoist from the seabed a diesel-electric powered Golf-II class Soviet submarine carrying five nuclear ballistic missiles. Designated K-129, this sub sank 1,560 nautical miles from Hawaii on March 8, 1968. The Soviet fleet searched in vain for their lost submarine. But the US Navy pinpointed its grave thanks to a network of underwater hydrophones that recorded its violent and sudden expiry. The Central Intelligence Agency was given carte blanche to salvage the wreck, its nuclear technology, and codebooks, regardless of the cost. Glomar Explorer was commissioned and using a clever smokescreen its true purpose was kept secret from the press, to its construction crew, and even more importantly to the Soviet Union. In the summer of 1974 the ship reached the site of the wreck and lowered a giant claw-like structure designed to grasp the demised sub from the sea floor some 4.9 km below![17] The recovery started well but a malfunction of the claw caused the sub to break and only a small portion of it was actually brought on board. It is a truly fascinating story which is not that different in complexity from retrieving a small asteroid and relocating it to a new orbit. And you would not have the challenge of keeping the entire project secret and devising a cover story!

Figure 7.12 The Glomar Explorer. The purpose of the imposing apparatus that covers its entire deck, particularly the derrick amidships, was officially ultra-deep ocean mining of manganese modules, but the true objective was secret.

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[17] To mask its mission, the area of the ship open to the sea (the so-called moon pool) was completely hidden from view and the claw (named Clementine) was brought to the ship from below at night without outside observers suspecting what was going on beneath the waves.

Once space-based resource have been extracted and processed, their elaboration into a useful product will be done in orbital factories where the properties of space can be put to good use. As more experience is gained, such industrial units will grow in complexity and scale, with numerous interconnected manufacturing units, tanks, robotic platforms, storage facilities, docking ports for visiting spacecraft, and so on. The International Space Station will seem small in comparison, in terms of acreage and intricacy. These orbital plants will match some of the most gargantuan industrial plants, such as the Shell Prelude, the largest floating liquefied natural gas (FLNG) platform yet to leave port. Its job is to process gas extracted in remote offshore fields where reserves are so sparse and in such low concentrations as to make installing a dedicated extraction facility unprofitable. In such fields, gas is extracted by subsea or surface platforms spread across the field, then routed to a floating platform where it can be processed, liquefied, and stored in internal tanks. This is an effective means of extracting gas and hydrocarbons in remote or deep water locations, where seabed pipelines leading to a land-based processing plant are not cost-effective. Therefore, such platforms eliminate the need to lay expensive long-distance pipelines from the processing facility to an onshore terminal. They provide an economically attractive solution for smaller fields, which can be exhausted in a few years and cannot justify the expense of a pipeline. Once the field is depleted, the platform can be moved to a new location. At full load, the 488-meter-long, 74-meter-wide Shell Prelude has a displacement exceeding 600,000 tonnes; more than five times that of a Nimitz-class aircraft carrier. Its construction consumed over 260,000 tonnes of steel. It has been designed to overcome the most severe weather conditions, including a category five cyclone. It can work in waters 250 meters deep and is held in place by four mooring chains that are held on the seabed by suction piles. Even a cursory glance at its layout shows the topside, bow to stern, to be a maze of pipelines, chimneys, and supporting structures, topped with large cranes. The facility freezes the produced natural gas to –162°C, which reduces its volume by 600 times. The tanks can hold a total amount of liquid equal to 175 Olympic-sized swimming pools. The natural gas, together with by-products such as liquid propane, is periodically offloaded to ocean-going carriers which deliver it to facilities on land.

It is clear that robotics will be necessary for most of the mining activities in space. On the Moon, given the short distance from Earth, telepresence and teleoperation are feasible but for a deep space object (even one of the Near-Earth Asteroids) the only sensible way will be to enable the machinery to operate autonomously, using remote human intervention only in circumstances where the programming faces a challenge it realizes it cannot resolve. Artificial intelligence will be heavily embedded into the programming. Once again, this is nothing new for Earth-based industries.

Figure 7.13 An overview of the Prelude floating liquefied natural gas (FLNG) facility, illustrating its sheer size and complexity.

Consider, for instance, Rio Tinto, one of the world's largest metals and mining corporations that has been operating automated haulage trucks, rock drilling rigs and trains at four mines in Australia. Driverless trucks are guided by GPS and use radar and lasers to spot obstacles. As they can drive themselves, they can spend more time working because the software does not require bathroom breaks or shift changes and it is not prone to human error. They are more predictable in their operation, meaning that more material can be moved more efficiently and safely. The trucks are steered by a supervisory system and a central controller that uses GPS to navigate roads and intersections while keeping monitoring the movements of the surrounding traffic. By the end of 2019 the company expects to operate more than 140 of these autonomous trucks. Telepresence also allows a human operator to handle remote automated blast-hole drill systems. Autonomous trains have been introduced to collect iron from 14 mines and deliver it to four port terminals. Virtually eliminating the need for a human driver has reduced the number of stopovers to change drivers. Furthermore, having done away with the acceleration and breaking commands typical of a human driver, the 2.4-km-long trains run 6% faster. In addition, because the software can be more predictable and gentle than any human in how it uses brakes and other controls, train maintenance savings have resulted. Other mining companies are rapidly introducing automation to save on time and operating costs and to increase revenues.

We could fill several volumes listing the marvels of human engineering, but I am sure that by now you have realized there are no projects too complex or gargantuan that they cannot be tackled by human ingenuity, especially when strongly motivated. It has been the case throughout the whole of recorded human history. Think about monuments such as the Pyramids of Egypt, the Great Wall of China, the cathedrals erected in Europe during the Middle Ages, and the majestic temples of Angkor in Cambodia. And then there are modern feats of civil engineering such as the Three Gorges Dam in China which has a span of 2.3 km, or the Burj Khalifa skyscraper in Dubai that rises 828 meters, or the transcontinental railroad laid in the 18th century for a distance of 3,000 km to connect the Atlantic and Pacific coasts of the United States with magnificent indifference to the terrain.

Seen in this light, our ability to meet challenges makes less daunting the prospect of mining the Moon or an asteroid, or manufacturing goods in space, even though at the moment these tasks may seem impossibly ambitious.

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8

For the Benefit of Humankind

THE BENEFITS OF SPACE RESOURCES MINING

The true motivation for space exploration is to take better care of our fragile planet. Archaeology shows how entire civilizations can collapse after failing to manage their limited resources and neglecting to repair the damage inflicted to the environment.

Look no further than Easter Island. In his book *Collapse: How Societies Choose to Fail or Survive*, American historian Jared Mason Diamond describes "the most extreme example of forest destruction in the Pacific, and among the most extreme in the world: the whole forest gone, and all of its tree species extinct. Immediate consequences of the islanders were losses of raw materials, losses of wild-caught foods, and decreased crop yield." For the islanders this was catastrophic. With their natural resources depleted they could no longer manufacture seagoing canoes with which to fish offshore; no longer protect themselves from the cold, windy winters by burning wood or building shelters; no longer continue to erect the statues that are characteristic of the island. Deforestation enabled the wind and rain to erode the soil and further deprive the islanders of local sources of food. This severely limited their farming. As Diamond continues, "They had the misfortune of living in one of the most fragile environments at the highest risk of deforestation of any Pacific people. … [The] formerly complex integrated society collapsed in an epidemic of civil war." Fights over control of the remaining resources, primarily plants and wood, led to one of the most repugnant of human acts: cannibalism.

Easter Island might be far in space and time from our reality but it is a compelling analogue of our modern society. The islanders were isolated, separated from the rest of the world's civilizations by the Pacific Ocean and hence unable to ask

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for help. In much the same way planet Earth exists in the infinite ocean of space, isolated from any other habitable world (if indeed one exists). They could not escape from their tiny territory, which they had made worthless. Similarly if climate change, pollution, and plundering of resources go unchecked and pose a severe threat to our existence we will be trapped. In concluding his analysis of Easter Island's demise, Diamond asks: "If mere thousands of Easter Islanders with just stone tools and their own muscle power sufficed to destroy their environment and thereby destroyed their society, how can billions of people with metal tools and machine power now fail to do worse?"

Another good example is the Chaco Anasazi, a society that dwelled in the Chaco Canyon of northwestern New Mexico for hundreds of years, beginning in 600 AD. As Diamond has written: "It was a complexly organized, geographically extensive, regionally integrated society that erected the largest buildings in pre-Columbian North America." They managed to tame a fragile desert environment characterized by low and unpredictable rainfall, quickly exhausted soils, and very low rate of forest growth. Then they collapsed. "Over the course of six centuries the human population of Chaco Canyon grew, its demands on the environment grew, its environmental resources declined, and people came to be living increasingly close to the margin of what the environment could support." In the wake of this collapse they were unable to rebuild their society in the way that the first farmers of that area had because "the initial conditions of abundant nearby trees, high groundwater levels, and a smooth floodplain without arroyos [rivers] had disappeared". If our modern industrialized globalized society were to collapse, would it rise again and regain its splendor?

Easter Island and the Chaco Anasazi were small civilizations, tiny compared to our interconnected world, and we might be tempted to sit on our laurels and persuade ourselves that our society is too large to fail. It might be so, but the fall of the Maya is a striking reminder that even well-developed, culturally advanced societies are not immune to collapse. Diamond identifies several reasons for their break down. For instance, "pollution outstripping available resources … too many farmers grew too many crops on too much of the landscape" causing pollution to outstrip any available resource until there was no land left unblemished. A second motive was "the effects of deforestation and hillside erosion, which caused a decrease in the amount of usable farmland at a time when more rather than less farmland was needed, and possibly exacerbated by an anthropogenic drought resulting from deforestation, by soil nutrient depletion and other soil problems." As the local climate changed, people were forced to move into new areas until, finally, "there was no useful unoccupied land in the vicinity on which to begin anew, and the whole population could not be accommodated in the few areas that continued to have reliable water supplies." I am sure that, by now, you will have recognized how alarmingly analogous the Maya are to our society!

Diamond's analysis of how civilizations collapse cites environmental damage as the chief culprit, no matter how sophisticated such societies were. He has arranged environmental damage into twelve categories: deforestation and habitat destruction; soil problems (erosion, salinization, and the loss of soil fertility); water management problems; overhunting; overfishing; introducing new species to native ones; human population growth; increased per-capita impact of people; climate change caused by humans; accumulation of toxic chemicals in the environment; energy shortages; full human utilization of Earth's photosynthetic capacity.

Some of these categories, particularly the accumulation of toxic chemicals in the environment and destruction of natural habitats, are heavily influenced by resource extraction and manufacturing industries. We saw in Chapter 1 how we are generally degrading the environment and overwhelming it with pollution. We are in danger of destroying the biosphere that is the life support system for our species.

We went to the Moon in response to a perceived political and ideological threat whose magnitude triggered a whole nation into Cold War battle mode and delivered an impossible dream: walking on the Moon. Now, the entire human species is under threat by a menace far worse than those ideological skirmishes. An appreciation of just how similar our modern society is to civilizations that collapsed catastrophically ought to make us regard space not only as a place of discovery but also as a valuable resource that can safeguard the long-term prospects of our species by turning it into a spacefaring civilization. This will, in return, relieve the stresses that we are placing on our planet.

Let us highlight again that a space-based manufacturing industry is not a panacea, a cure for all of humankind's misconduct, but it does have the potential to be a part of the solution. Off-world mining will initially parallel its terrestrial counterpart, then become our main supplier of resources. Remember in the lifeless vacuum of space, resource mining is environmentally harmless.

By accessing the immense resources of the Solar System, extraterrestrial mining might also play a role in alleviating the political pressures that result from resource scarcity, an issue that it is receiving ever more consideration. In their book *Scarcity: The True Cost of Not Having Enough*, Sendhil Mullainathan and Eldar Shafir explain how "scarcity captures the mind … it changes how we think. It imposes itself on our minds … having less is unpleasant … scarcity leads to dissatisfaction and struggle." And "because we are preoccupied by scarcity, because our mind constantly returns to it, we have less mind to give to the rest of life … it makes us less insightful, less forward-thinking, less controlled … focusing on one thing means neglecting others." In effect, scarcity causes us "to focus single-mindedly on managing the scarcity at hand."

Indeed, we are resorting ever more often to this single-minded management by way of declarations of economic sanctions; trade wars; establishment of outposts in territories whose jurisdiction is widely contested because they can offer a strategic advantage in controlling key resource supplies or commercial routes; and agreements between governments and corporations for the exclusive exploitation of land and its resources, often disregarding the local population and the possibility of armed local conflicts. As it is often the case, such arrangements involve countries that are laden with corruption and have essentially no interest in the welfare of their citizens or the preservation of the environment. Eventually, as the effects of resource scarcity are felt by our society this could all too readily precipitate conflicts on a much grander scale as individual nations seek to protect their interests by assuring access to crucial resources regardless of the consequences. Remember the Maya? Another cause for their disintegration was, as Diamond says, the "increased fighting, as more and more people fought over fewer resources. Maya warfare, already endemic, peaked just before the collapse. … Warfare would have decreased further the amount of land available for agriculture, by creating no-man's lands between principalities where it was now unsafe to farm." We would do well to pay attention to how resource scarcity might one day steer us to the same fate.

We could intensify our efforts to exploit lower-grade ores, presuming that we are willing to accept a few nasty consequences. For instance, resource mining is mostly a matter of energy rather than quantity. This is why we first exploited the high-grade ores. Because they are easily accessible they are not particularly demanding in terms of the energy required to extract and process them. By contrast, low-grade ores are being surveyed and exploited only now because they do necessitate more energy for their extraction. This requires increasingly sophisticated equipment to be transported and then assembled in punishing places – remember the Shell Prelude? It must be designed to work in a more hostile environment – remember the Berkut oil rig? In general, if an ore has a concentration ten times lower than a richer one it will demand ten times more energy to extract the same quantity of resource. What about waste? The poorer the concentration of ore, the greater is the quantity of rock and soil to be displaced and processed, as well as the chemicals needed for beneficiation. Thus we escalate pollution and environmental degradation. Besides, as Ugo Bardi, a professor of Physical Chemistry at the University of Florence, Italy, reminds us in his book *Extracted: How the Quest for Mineral Wealth is Plundering the Planet*, "The total energy used by the mining and metal-producing industry might be close to 10 per cent of the total world energy production [and] this can only increase as we access lower-grade resources." So we see that resource scarcity and energy production are interlinked. Indeed, as Bardi points out, "The problem of dwindling ore grades also occurs with the fossil fuels; energy is becoming more and more energy-expensive to produce." This includes energy produced by solar, tidal, and wind resources. Unless we can generate more energy to account for the increased demand imposed by the exploitation of lower-grade ores, resource scarcity will continue to pose a threat to society. At the same time, boosting the demand for energy can only cause additional environmental damage, as the already dwindling resources required for the energy-producing apparatus, such as solar panels, windmills, batteries, and power lines, are being extracted from low-grade ores.

A circular economy that makes the most of available resources while minimizing waste has undoubted merits but it is not immune from shortcomings. Bardi reminds us, "In most places around the world there has never been an effort to manage waste in such a way to make it easy to recover useful materials from it … as a consequence many minerals that have entered the world's economy during the past few centuries are today accumulated inside landfills or dispersed in the ecosystem … Reclaiming the minerals from waste that we have recklessly dispersed around or even dumped into the ocean is a monumental task, and it is unlikely we could reasonably recover much of them … The average concentration of rare metals in a landfill is low. An even more difficult problem is that metals are mixed together. So exploiting a landfill as if it were a mine would require sophisticated and expensive separation techniques and much energy, and would also create a lot of pollution." Mining landfills is not without risks, as it brings its own drawbacks in terms of workers' safety and enduring organic waste that produces foul odors and bacterial contaminations. Also, landfills contain all manner of sharp-edged objects, poisons, explosives, noxious gases, and many more potential hazards. Bardi also warns of "downcycling," a term that "refers to the fact the recycled material is normally of lower quality than the same material manufactured from pristine mineral sources". For example, consider the aluminum in cans for foods and beverages. Often it is alloyed with magnesium. Separating the metals for reuse involves a great effort. Another representative case is that of steel. As the application drives the formulation of each type of steel, it follows that melting together components made of different types of steel would result in steel of lower quality due to the presence of uncontrolled quantities of alloying elements, making the recycled steel an average of the input steels and thus not suitable for demanding structural applications. The bottom line, Bardi says, is that, "Most materials are not endlessly recyclable." In addition, "Recycling processes also require energy, water, and often the input of additional resources. Recycling also creates burdens through collection, reclamation, and transportation." Consequently, "Something that is truly unavoidable in our future is the disappearance of high-grade ore and the dispersal of the elements they contained all over the planet in forms that cannot be recovered."

Substitution is another approach but it, too, has its limitations. For instance, some elements have properties so peculiar that identifying a substitute might be impossible for given applications unless we invent a new metallurgy or new materials physics. Besides, the resources problem is one of confronting general scarcity not of merely coping with the exhaustion of one or two particular minerals. To illustrate, if we wish to replace copper with aluminum in electronic applications, the demand on resources would simply shift to aluminum, which will then be depleted even more rapidly than projected. And if a substitute is less efficient this will require a change in the design of a given application, possibly causing it to draw more energy to perform the same function. It is easy to appreciate how, for consumer applications, substitution might quickly *accelerate* resource depletion and provoke soaring energy requirements that have the opposite effect to that being sought.

The exploitation of low-grade ore, recycling, reuse, and substitution, are all valid policies for stalling resource scarcity and are worth exploring whenever feasible, but it must be kept in mind that they are not exempt from drawbacks or limitations due to physics and chemistry. Space resource mining could overcome these barriers, or at least assist in compensating for them, and thus enter into the mix of solutions that address our society's future resource and energy needs whilst caring for the planet's environment. Space mining will be conducted in an environment where energy from the Sun is abundant, continuous, and free. The exploitation of low-grade ores will be worthwhile on celestial bodies. Space mining will be able to supply the resources for which substitution and downcycling fall short.

THE BENEFITS OF MANUFACTURING IN SPACE

Because orbital factories will be in the vacuum of space they will supplement their terrestrial counterparts without endangering a life-filled environment. Their heat and waste cannot cause harm, because they will not interact with any biosphere.

Sunlight will be an inexhaustible source of energy to run power-hungry facilities. What goods will be produced? Ideally, anything! More practically, the first task of space-based manufacturing will be to demonstrate several high-tech applications of the type discussed in the previous chapter. Then, it can concentrate on producing a limited number of goods for terrestrial consumption that are in demand at that time; e.g., batteries for electric vehicles, computers and electronic devices. As is often said, "The sky is the limit." As the possibilities are endless, we should not limit ourselves in speculating what might or might not be manufactured.

In fact, factories in space offer the potential of constructing and assembling large infrastructures, such as satellite solar-power systems. This concept was patented by Peter E. Glaser in December 1973. US patent #3,781,647 says, "The radiation energy derived from the Sun is converted to microwave energy in equipment maintained in outer space, then it is transmitted as microwave energy to suitable collectors on Earth. Hence, the problems of absorption of the solar radiation by the atmosphere and of sudden interruptions are eliminated because microwaves can pass through the atmosphere with minimum absorption and scattering. By receiving the solar energy and converting it into the form of microwave energy, the microwave energy can be collected in widely dispersed locations on Earth without regard to availability of solar radiation. … Hence the major drawbacks associated with the direct terrestrial collection of solar energy are minimized." Ever since it was proposed, the concept has been studied in detail both by NASA and industry. Configurations and variations on the theme abound in the specialized literature. But the sheer size of the orbiting solar collector (several square kilometers) has always obliged the concept to remain on paper. Simply put, assembling such a large-scale infrastructure with components made on Earth would require so much material and so many launches as to make it unrealistic. The drawbacks would greatly outweigh the advantages. Yet, the concept will become viable if extraterrestrial resources and space manufacturing are adopted. Estimates vary, but some number of satellite solar-power systems could comfortably provide the energy to power our society and help elevate developing countries to the level of prosperity enjoyed by their developed counterparts.

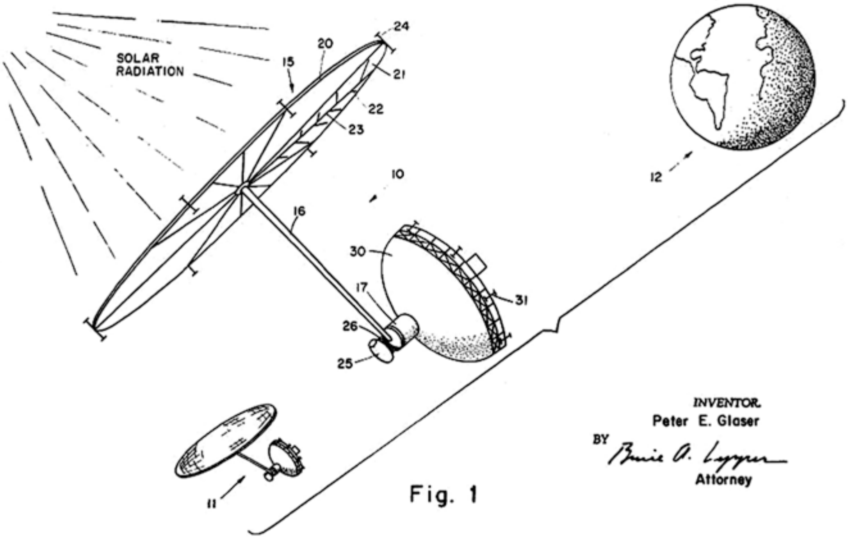

Figure 8.1 A depiction of the solar power satellite system envisioned by Peter Glaser in the patent application 3,781,647. Solar energy is gathered by a large collector and converted into microwaves that are then beamed to the surface. Not shown is the receiving antenna where the microwaves are converted into electricity and thus dispatched to the end users. For maximum efficiency, satellite solar-power systems were to operate in a geostationary orbit, so that they could always face the same receiving point on the surface. An attitude control system would maintain the collector facing the Sun.

Gerard K. O'Neill and many of his followers (including this author) look forward to colonies in space capable of housing millions of people. It will take some time to get there, but in the interim a practical application that is on a par with satellite solar-power systems is that of space farms.

As American journalist and educator Richard Heinberg wrote in his book *Peak Everything: Waking Up to the Century of Decline*, agriculture "is now the single greatest sources of human damage to the global environment. This damage is in the form of erosion and salinization of soil; deforestation (a strategy for bringing more land into cultivation); fertilizer runoff (which creates enormous 'dead zones' around the mouths of rivers); loss of biodiversity; fresh water scarcity; and agrochemical pollution of water and soil." This means that more food production to feed an ever-growing population is not a viable solution if we are to preserve the environment.

As Eric Zencey pointed out in his book *The Other Road to Serfdom and the Path to Sustainable Democracy*, a positive feedback exists in which "food scarcity leads to expanded agriculture, which diminishes natural ecosystems and their ecosystem services, which eventually leads to agricultural losses, which leads to food scarcity. … We could try to bring even more land into cultivation – but only at the cost of increasing the rate at which we lose something else, [namely] the ecosystem services on which our civilization, including our capacity to feed ourselves, depends."

Besides, the amount of food we can grow is limited by three factors: soil fertility, water, and sunlight. As Zencey continues, "In our cheap-energy petroleum economy we've pushed against the limits set by the first two constraints, using the energy of oil to fix nitrogen into artificial fertilizers and to pump fresh water into dry lands that are, in nature's design, inhospitable to farming. … When the oil runs out, so too will end its enormous subsidy to agriculture."

As far as sunlight is concerned, the Sun will keep shining for billions of years to come, so we will not have to bother with absence of sunlight any time soon. Still, we do need to consider that sunlight is the driver of photosynthesis, which is a complex sequence of chemical reactions that enable plants to grow food. Considering that the Earth's surface is finite and that only a limited portion of it is suitable as arable land there is a limited capacity of growing food, for humans and all other living species. In the same manner that resource scarcity and environmental concerns can drive the exploitation of extraterrestrial resources, farming in space will alleviate the pressure imposed on the environment by the need to feed an ever-growing population. Space farming would also be immune from the vagaries of natural phenomena, often driven by the climate change that we are ourselves causing, such as flooding and droughts. When large areas assigned to agriculture are hit by such events, the resulting loss in food production can have repercussions on the well-being of a whole nation, perhaps even wider, depending on the kind of crops that are lost. Often the recovery is slow, and can be further delayed if another natural disaster strikes in the meantime.

As of today, only a small number of puny investigations have been carried out in the field of space farming. The focus is on achieving a better understanding of plant behavior in zero-g, and giving a therapeutic past-time to astronauts on long-duration missions. Interest is growing, spurred by the ever-present willingness to establish a small scientific outpost on the Moon or on Mars. Clearly, space farming will require serious attention, as well as the establishment of a development program not unlike that for orbital factories. A good starting point would be to research the best ways to grow food in space on an industrial scale, to assess whether it is feasible in zero-g or requires a level of artificial gravity. Terrestrial approaches such as hydroponics and vertical farming would surely be among the favorite candidates for trial in space. At first the greenhouse modules could be manufactured on Earth and launched to create a space farm of several modules. This would help to grasp the working principles of an infrastructure dedicated to growing food, instead of the manufacture of products. In time, as space-based manufacturing evolves, such modules could be fabricated in-situ, perhaps using minerals supplied by off-world mines. The first space farms could be designed to grow staple and non-perishable food. Eventually, they would house livestock. Once again, the sky is the limit. And considering that space farming will require us to artificially recreate and maintain a terrestrial habitat, such applications might help us to find better solutions for taking care of Earth's natural environment.

AIMING AT THE FUTURE

Becoming a space-faring civilization is not going to be easy. There will be plenty of trial and error, lots of opportunities for mistakes, dead ends, and the like. Nor will it be rapid. The first decade of human space exploration kicked off with Yuri Gagarin's single orbit and concluded with humans walking on the Moon. It is unlikely that the development of space-based manufacturing will follow such a meteoric growth, but that is fine because we are not talking about merely planting flags on other worlds and bringing back a few specimens. Instead, the aim is to profoundly alter the current paradigm of space exploration in which off-world activities appear only in the realms of basic science, technology applications, and support of prospective future missions to the Moon and Mars. In the new paradigm, space is a potent ally that supports our stewardship of Earth and its unique biosphere.

We can compare the inception of space-based manufacturing to the onset of the First Industrial Revolution in the 18th century, marked by the appearance of the first steam-powered machines in the north of England to pump water out of deep mines. The engineering creativity that gave rise to a vast range of mechanized systems and new manufacturing processes led directly to modern society. When in 1712 Thomas Newcomen introduced the first successful piston engine it is highly unlikely he had any inkling that his apparatus would mark the beginning of an industrial movement which, some 250 years later, would give humankind the tools to walk on the Moon. The same goes for the other engineers who were tinkering with steam, new materials technologies, novel manufacturing processes, erection of bridges and buildings, and the like. Our modern society emerged from this creativity without a clear masterplan.

Even the most talented futurist will therefore struggle to predict exactly how our society will look 250 years from now. We cannot pretend to specify in minute detail every step in the establishment of a space-based manufacturing industry. Rather, we can identify the hurdles that will need to be overcome (as discussed in the previous chapter) and chart the best courses of action to expedite progress. Think of an artist and the planning that occurs before putting paint to the canvas. It requires producing sketches, studying shapes, geometry and illumination, composing the scene. If it is done properly the result might be a masterpiece.

In developing space infrastructures, we are still at the preliminary planning phase. We have an idea of what we want but have only sketches to help us get started. That is why the previous chapter highlighted some of the main roadblocks to be addressed but didn't specify which mining methodology should be used first, or which zero-g manufacturing process should be trialed first, or what the first space factory should be designed to produce. Only an IOSD-like organization would have the brain-power and capability to answer these questions, assess results of trials, and gain confidence. In contrast to the First Industrial Revolution, we at least have the benefit of a sketchy outline of a plan.

We are accustomed to fast-paced innovation reaching our households in the form of consumer technology such as smartphones, autos, computers, and the like. But the same rapidity of innovation and obtaining favorable results will not characterize the establishment of a space-based manufacturing industry. As the engineers of the First Industrial Revolution had to battle mechanical failures, structural collapses, blowing up of pressure vessels, and the like, so we must recognize that there will be failures and we shall have to endure these setbacks with perseverance and tenacity. This will be particularly difficult when lives are lost.

This means that we should not fixate on deadlines, because progress rarely obeys our projections. "Kennedy moments" belong to the past and, as a matter of fact, they only serve as a political agenda for administrations to earn votes at the next elections. As noted in Chapter 1, several administrations tried to ordain specific dates and each failed. Trying to force the pace of progress, especially for projects of this magnitude, will be senseless. That is why we cannot answer the question of "when" all of this is going to happen. It will take several decades merely to activate a rudimentary orbital industry that is sufficiently proficient to support itself with extraterrestrial resources. The chances are that you and I will no longer be around to see all of this happen, but surely by the end of the century space mining and manufacturing will have become integral to society.

Living in an economic system based on profit and driven to produce continuous growth, the inevitable question will be: how much it is going to cost? The outcome of such an endeavor is so far in the future that it demands that we, as a society, stop thinking only in terms of economic profit/benefit and start to recognize that we have the moral obligation to leave a better planet to our offspring, no matter the monetary cost.

Does the human race have the moral authority to sacrifice the well-being of the planet simply because it would not be profitable on our current economic models?[1] As Zencey argues, "In their enthusiasm for the admittedly impressive ability of free-market capitalism to generate wealth and thereby raise human society to heights of material comfort, mainstream economists have ignored this fundamental physical truth: economic activity takes in valuable matter and energy from its environment and discharges degraded matter and energy back into it. Because the planet itself is finite, its capacity to sustain either flow without ecological degradation is finite." It is time to make our priority the preservation of our biosphere and the habitability of our planet, and abandon economic models that blatantly ignore resource scarcity and environmental damage.[2]

This is why I purposely avoided discussing any influence that off-world mining and manufacturing might have on the global economy, as such changes will be far-reaching and so pivotal that it would be pointless to attempt a forecast now. Like so many initiatives and strategies aimed at curbing emissions, reducing environmental damage and fighting climate change, we cannot put a price on preserving our planet's biosphere in a state that will enable our species to survive.

A common objection presented against colonizing space is that we should resolve all the problems we have on Earth before spending resources on a boondoggle in the sky. The answer is simple. By the time we have achieved such a noble intent, it might be too late for the environment and society. If we do not exploit the resources which await us in space, the chances are that we become trapped on an inhospitable Earth. Our current civilization would certainly not survive and our species might even go extinct.

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[1] If you doubt this, consider why corporations prefer to invest in countries whose environmental control laws are either non-existent or not as stringent as in the Western world? Or why corporations are lobbying certain developed countries to relax their current rigorous environmental regime?

[2] There is a growing movement related to post-capitalism growth and ecological economy seeking to develop new economic models that are funded in the reality of a planet with finite resources and an environment that is in need of protection. If you are interested in this topic then Eric Zencey's book *The Other Road to Serfdom* (quoted in this chapter) is a good starting point.

Figure 8.2 Reflecting on his experience of admiring Earth from the Moon, astronaut Edgar D. Mitchell of the Apollo 14 mission remarked: "You develop an instant global consciousness, a people orientation, an intense dissatisfaction with the state of the world, and a compulsion to do something about it." Let us build a space program for the benefit of humankind and our home planet.

We have to start thinking in terms of a vision for a better future, to continuously remind ourselves that – just like the inhabitants of Easter Island – Earth is the only hospitable island that can keep humankind alive. Indeed, as far as we know it is the only planet in the Universe to have such a diverse biosphere. We protect artefacts that we consider to be worthy of preservation for future generations, and we have a similar obligation to safeguard our planet and everything that is on it. A great many talented people are working to make our home in the Solar System a better place. I hope this book has shown that space resources and off-world manufacturing are part of the solution. Let us safeguard the future of our planet and our species with a space program that is worth undertaking!

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IMAGE LINKS

Figure 8.1: Method and apparatus for converting solar radiation to electrical power. (1973). Patent 3,781,647.

Figure 8.2: https://www.flickr.com/photos/nasacommons/5052124705/in/album-72157625096855580/

About the Author

Davide Sivolella is an aerospace engineer living and working in the UK as a specialist in the design of structural repairs for civil airliners. Currently is lives near London with his Spanish wife, Monica. As a child, Davide developed a fascination with all manner of flying machines, especially those which traveled above the atmosphere. In fact, this passion for astronautics and space exploration led to bachelor's and master's degrees in Aerospace Engineering from the Polytechnic of Turin (Italy). Having been born in 1981, just a few months after the maiden flight of Columbia, he developed a fondness for the Space Shuttle. This led to Springer-Praxis publishing his first book in 2013, *To Orbit and Back Again: How the Space Shuttle Flew in Space*. It was followed in 2017 by *The Space Shuttle Program: Technologies and Accomplishments*. In recent years, he has researched how space exploration can foster a practical solution to help us ease the most excruciating problems affecting Earth and humankind, such as environmental pollution, climate change, and resource depletion. On several occasions Jeff Bezos, the founder of both Amazon and Blue Origin, has stated that he envisions a future where the manufacturing industry will be relocated into space to exploit the resources of the Solar System. Davide's research has convinced him that this vision is indeed capable of delivering benefits which current plans for human exploration of the Moon or Mars do not address. That was the motivation for writing this book.

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Index

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