The Commercial Lunar Economy Field Guide

A Vision for Industry on the Moon in the Next Decade

Edited by Michael Nayak

With perspectives from S. Pete Worden & Jay Raymond

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Air University Press
Maxwell Air Force Base, Alabama

Air University Press

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Air University Press
600 Chennault Circle, Building 1405
Maxwell AFB, AL 36112-6010
https://www.airuniversity.af.edu/AUPress/

Facebook: https://www.facebook.com/AirUnivPress

Instagram: https://www.instagram.com/air_university_press/

LinkedIn: https://www.linkedin.com/air-university-press

X: https://x.com/aupress/

Library of Congress Cataloging-in-Publication Data
Names: Nayak, Michael editor | Air University (U.S.). Press issuing body
Title: The commercial lunar economy field guide: a vision for industry on the Moon in the next decade / edited by Michael Nayak.
Other titles: a vision for industry on the Moon in the next decade
Description: [Maxwell Air Force Base, Alabama] : [Air University Press], 2025. | "With perspectives from S. Pete Worden & Jay Raymond." | Includes bibliographical references. | Summary: "The Defense Advanced Research Projects Agency in partnership with the Johns Hopkins Applied Physics Laboratory and key participants in the space community investigate what it takes to develop a functioning lunar economy"— Provided by publisher.
Identifiers: LCCN 2024055917 (print) | LCCN 2024055918 (ebook) | ISBN 9781585663323 paperback | ISBN 9781585663323 Adobe pdf
Subjects: LCSH: United States. Defense Advanced Research Projects Agency | Space industrialization—United States | Moon—Exploration—Economic aspects | Outer space—Civilian use
Classification: LCC HD9711.75.U62 (print) | LCC HD9711.75.U62 (ebook) | DDC 338.0999—dc23/eng/20241216 | SUDOC D 1.2:L 97 LC record available at https://lccn.loc.gov/2024055917 LC ebook record available at https://lccn.loc.gov/2024055918

Published by Air University Press in 2025

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Foreword

The Department of Defense (DOD) has long played a foundational role in advancing space capabilities, often in partnership with civil space programs. Early pioneers of US space exploration, like John Glenn and Neil Armstrong, were military test pilots whose experiences shaped civil missions such as Mercury, Gemini, and Apollo. Their achievements underscore a tradition of collaboration that continues to drive innovation and exploration.

The DOD's impact on space exploration extends beyond its personnel. Pivotal missions like the 1992 Clementine "return to the Moon" highlight the department's broader contributions. This joint mission between the Ballistic Missile Defense Organization (BMDO) and NASA marked the United States' first lunar venture in two decades. Clementine provided critical data on lunar topography and composition, including the first evidence of significant water ice in the Moon's polar regions. This groundbreaking discovery revolutionized our understanding of the Moon's resources and its potential to support sustained exploration.

Building on such milestones, the US National Cislunar Science and Technology Strategy provides a framework for coordinated efforts by NASA, the Department of Commerce, the Department of State, commercial industry, international partners, and the DOD. It emphasizes creating a sustainable and secure presence in cislunar space by leveraging unique capabilities across stakeholders. The LunA-10 study builds on this foundation, with DARPA leveraging its expertise to explore the economic potential of the Moon while addressing the challenges of sustainability in cislunar space.

The insights shared in this book are enriched by the invaluable contributions of General John W. Raymond (retired), former Chief of Space Operations of the United States Space Force, and Brigadier General Simon "Pete" Worden, PhD (retired), of the United States Air Force. Drawing on their distinguished careers, they offer critical perspectives on the importance of lunar exploration, adding strategic depth to the LunA-10 study.

As the Principal Director for Space Technology within the Office of the Under Secretary of Defense for Research and Engineering, it is my honor to introduce the LunA-10 study. I extend my deepest gratitude to Dr. Philip Root and Dr. Michael Nayak of DARPA for their exceptional leadership and vision. Their work has been vital in shaping this blueprint for the lunar economy, laying the groundwork for progress in this promising frontier.

BRYAN DORLAND, PhD
Principal Director for Space Technology
Office of the Undersecretary of Defense for Research and Engineering

PART 1

HISTORICAL AND FRAMING PERSPECTIVE

1

From Flags and Footprints to a Commercial Lunar Economy

S. Pete Worden

Dr. S. Pete Worden is the chair of the Breakthrough Prize Foundation. He is a US Air Force retired brigadier general with a distinguished list of space accomplishments, to include commanding the Fiftieth Space Wing (60+ Department of Defense satellites and 6,000+ people at twenty-three worldwide locations), and the Clementine satellite mission, which orbited the Moon. He has also served as the Director of the NASA Ames Research Center in Silicon Valley and as a scientific co-investigator for three NASA space science missions. Today, he is recognized as an innovator and space disruptor and is actively engaged in building partnerships between governments and the commercial sector, both in the US and internationally.

I was nineteen, between my sophomore and junior years of college, when our nation landed the first humans on the Moon. It was the most inspirational moment of my then young life—and it still is. I remember my dad's best friend asking me if I thought I'd ever fly to the Moon. I said, "Most certainly yes." In fact, I went further than that. I said we'd have human missions to Jupiter and beyond by 2000. By 2025, we'd be on our way to the stars.

Sadly, I was mistaken. Many of us who grew up on Apollo were frustrated by the ensuing slow pace. A few decades ago, I referred to NASA as a "self-licking ice cream cone." That has all changed. NASA is no longer your grandparents' space agency. We are going back to the Moon in full partnership with the private-sector space community. And it's a truly global partnership.

The Apollo program opened the lunar era. NASA and other government science and exploration missions since have characterized the Moon. I have been privileged to play a leadership role in three robotic missions to the Moon: The Department of Defense's 1993 Clementine mission, America's first lunar mission since Apollo, gave us our first indication of lunar water ice; NASA's 2009 LCROSS mission confirmed substantial quantities of water at the lunar poles; and the 2013 LADEE mission studied the Moon's dust environment.[1]

Today, our return to the Moon is based on commercial partnerships, starting with privately developed launch capabilities. NASA's innovative Commercial Lunar Payload Services (CLPS) program is opening the lunar surface for private and government use at an affordable level. We are entering the next step—the commercial development of the Moon—soon to be followed by large-scale human settlement. This is mankind's next phase. We will soon be a truly interplanetary species and, not long after, an interstellar one.

The Commercial Lunar Economy Field Guide focuses on this commercial future. The Moon represents an expanding future, both for our country and our civilization. Lunar resources will first enable expanded activity, including lunar settlement. Fuel produced on the Moon will propel us to Mars and beyond. Resources extracted from the Moon, especially rare earth elements and platinum group metals, will be imported to Earth to sustain and advance the terrestrial economy. Energy produced or enabled by the Moon could even power our planet. It's the future I'd hoped for as a young college-age teenager.

Our future lunar program and operations in cislunar space are a full partnership between civil and commercial programs, with support from the national security community. The Department of Defense, in coordination with its partners in NASA and Department of Commerce, supports space situational awareness throughout cislunar space. Particularly as the number of lunar vehicles creates an increasing hazard of inadvertent collision or the need for rapid deconfliction, a top priority will be complete space situational awareness throughout cislunar space to support the difficult job of space traffic management (STM). DARPA's focus on cislunar and lunar technologies and capabilities is noteworthy and a significant furtherance of a long-standing role that started with the 1958 F-1 engine flown on Saturn V, one of DARPA's first endeavors.

Today, NASA's Artemis program is the first truly global exploration program. The Artemis Accords have forty-three signatories. They explicitly allow and encourage global commercial activities. Although some nations still criticize the approach, the Artemis Accords are in full compliance with the Outer Space Treaty. It is likely that the Artemis Accords will go down in history as a seminal step in human expansion into space. They will evolve into a truly global consensus on our shared future in space. This book outlines the strong legal and policy case for this economic approach. Global interoperability (chapter 22) will be key.

This compendium introduces some of the most significant technological aspects of a lunar economy. I'd like to highlight one, worthy of future exploration, explored in this *Field Guide*. Past studies of large-scale human use and occupation of celestial bodies generally feature programmable self-replicating machines. This concept was formulated by mathematician John von Neumann in 1948. With rapid advances in biological sciences (chapter 20), particularly synthetic biology, programmable organisms are in fact von Neumann machines. They can enable large-scale manufacturing and expansion on the Moon.

One of the key limitations to even faster and more robust use of the Moon is the rocket equation. Today, we are limited by the efficiency of chemical rocket engines. This may soon change. Efficient electric propulsion, with an order of magnitude greater thrust efficiency, is already in use but is low thrust. This is ideal for moving goods on which there is no time constraint. However, robust commercial development requires speed as well as efficiency. Nuclear-thermal fission engines are under development. Nuclear fusion—two orders of magnitude more robust than chemical engines—is on the horizon. Just as the introduction of jet-turbine aircraft engines revolutionized air transport, I believe these nuclear propulsion systems will revolutionize our economic activities in cislunar space.

Cislunar activities and settlement, led by commercial endeavors, are opening a new era in American and global development. This is the long overdue follow-on to NASA's Apollo program. The global inclusiveness of the Artemis Accords is a major policy milestone. The new technologies being harnessed to extract and use lunar resources, supported by the numerous commercial endeavors covered in this book, are impressive. We are on the verge of a new era.

Expanding first into cislunar space and then making use of the Moon and its resources would move us from a growth-limited terrestrial future to an open, unlimited space future. The DARPA 10-Year Lunar Architecture (LunA-10) studies are major milestones in seeding this future. If you read just one compendium about the new lunar economy, this is it!

Endnotes

1. LCROSS is Lunar Crater Observation and Sensing Satellite; LADEE is Lunar Atmosphere and Dust Environment Explorer.

2

Strategic Perspective: The LOGIC behind LunA-10

Philip Root

Dr. Philip Root is the Director of DARPA's Strategic Technology Office. He leads a team of technologists and thought leaders with the stated mission to disrupt current national security paradigms, avoid surprise, and maintain advantage against peer threats. His DARPA tenure began as a Program Manager in the Tactical Technology Office, where he led a portfolio at the intersection of robotics, AI, autonomy, human-machine teaming, and ethics. He has served as Deputy and Acting Director of the DARPA Defense Sciences Office. Root started his career as an Apache helicopter pilot in the US Army, followed by tours with NASA and in Afghanistan, completing graduate degrees at the Massachusetts Institute of Technology and serving as faculty at the United States Military Academy.

2.1 Framing the Moon, and International Lunar Pursuits

The Soviet launch of the Sputnik satellite in 1957 immediately shook the Eisenhower administration. Four months later, the administration created the Advanced Research Projects Agency (ARPA), renamed DARPA in 1972, with the stated goal to prevent technological surprise. Soon thereafter, in July 1958, Congress launched NASA to repurpose existing defense-related research toward civil space "without delay." DARPA and NASA have shared technological DNA ever since. In the sixty years since, these independent agencies have coordinated on multiple research programs related to hypersonic flight, autonomous systems, vertical lift technologies, and rocket propulsion development.

The Sputnik launch and the ensuing race in US-Soviet intercontinental ballistic missile launch capability also shook the international community. The Outer Space Treaty (OST), formally the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, ratified in 1967, was born in this same environment of surprise, anxiety, and heightened tensions. The treaty's preamble, however, perfectly captures the distinct human relationship with space, and the Moon in particular:

> Inspired by the great prospects opening up before mankind as a result of man's entry into outer space,
>
> Recognizing the common interest of all mankind in the progress of the exploration and use of outer space for peaceful purposes,
>
> Believing that the exploration and use of outer space should be carried on for the benefit of all peoples irrespective of the degree of their economic or scientific development,
>
> Desiring to contribute to broad international cooperation in the scientific as well as the legal aspects of the exploration and use of outer space for peaceful purposes,
>
> Believing that such cooperation will contribute to the development of mutual understanding and to the strengthening of friendly relations between States and peoples.[1]

The treaty, including its seventeen subsequent articles, became the foundation for international outer space law. The world has witnessed epochal changes during the sixty years since OST ratification. The Cold War nearly spilled over from crisis into conflict on several occasions before the Soviet Union collapsed; the Berlin Wall fell and the Europeans united; America enjoyed a brief unipolar moment; Korea and Japan greatly expanded their industrial output; and the Chinese lifted nearly their entire nation out of poverty to become a political, economic, and technological peer. Despite these changes, the preamble of the OST still aptly captures the unique relationship between humanity and outer space.

It is worth considering how spacefaring nations choose to name their lunar programs. Whereas the Soviets chose literal names like Lun ("moon"), Lunokhod ("moon walker"), and Zond ("probe"), most other spacefaring nations chose names associated with Moon-centered mythological or divine figures. The Japanese Kaguya orbiter derives its name from the lunar princess from Japanese folklore. American space programs Apollo, and more recently Artemis, are derived from Greek mythology for the Sun and Moon god and goddess, respectively. Chandra is both the Hindu god of the Moon and the root word of the Indian Chandrayaan lunar missions. Finally, while the Chang'e lunar missions arrived on the lunar surface less than twenty years ago, Chang'e first appeared in Zhou dynasty writing over three thousand years ago as the goddess of the Moon.

This brings up an almost philosophical question: How do we proceed in an era when scientific and technological advances have pulled lunar exploration within reach for so many spacefaring nations, but a simmering great power competition threatens to overshadow these achievements as geopolitically motivated? How can we navigate to a future where human civilization can continue to revere the Moon without threat of exploitation or hegemony, in line with the Outer Space Treaty's preamble and articles?

2.2 Framing the DARPA Strategic Perspective

Given DARPA's unique mission, the above philosophical question can be rephrased as: Can we prevent the surprise unraveling of international consensus and instead chart a path toward continued international lunar cooperation with responsible, peaceful, and sustainable exploration? Can we create and foster the conditions such that "cooperation will contribute to the development of mutual understanding and to the strengthening of friendly relations between States and peoples,"[2] as outlined in the OST preamble?

DARPA faced a similar conundrum when first proposing to research and demonstrate the ability to perform in-flight refueling and repair for satellites in geosynchronous orbit. The international standards for such space proximity operations did not exist, and DARPA sought to navigate to a future where such services could be broadly commercially available. While the Robotic Servicing of Geostationary Satellites (RSGS) program sought to overcome the difficult technical challenges associated with robotic servicing, the agency in parallel launched the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS).[3]

CONFERS had the goal to create, research, develop, and publish "non-binding, consensus-derived recommendations for technical and operational standards for rendezvous proximity operations (RPO), on orbit servicing (OOS) and in space assembly, servicing, and manufacturing (ISAM)." In 2020, the CONFERS consortium transitioned from being primarily DARPA- and NASA-led to becoming "the independent global trade association developing industry-led recommendations for standards and guiding international policies for satellite servicing that contribute to a sustainable, safe, and diverse space economy."[4] In short, while the RSGS program tackled technical challenges, the CONFERS consortium tackled the remaining challenges: the policy and standards necessary to firmly establish the desired future, thereby resulting in a new and sustainable international community.

This successful RSGS-CONFERS programmatic structure was leveraged when DARPA Program Manager Michael Nayak was considering how to structure DARPA's LunA-10 program.[5] Technical challenges abound when drafting potential future lunar business models, and LunA-10 waded directly into this technical fray with a wide set of analytical and engineering studies. You will read about these results in part 2 of this *Field Guide*.

To foster a sustainable future of lunar exploration, DARPA launched the Lunar Operating Guidelines for Infrastructure Consortium (LOGIC) to begin the long-term and inclusive discussions surrounding commercial and international interoperability frameworks.[6] DARPA leveraged the NASA-sponsored Lunar Surface Innovation Initiative Consortium to maximize alignment with NASA's Moon-to-Mars Architecture and catalyze the creation of LOGIC.[7] At the time of this writing, over 1,000 participants from forty-four countries have participated in LOGIC discussions. More details on LOGIC are presented in chapter 22 of this *Field Guide*.

Thus, while this book highlights the technical achievements discovered during the LunA-10 studies, the related LOGIC community and standards development represent a unique contribution to a peaceful, sustainable, international future on the Moon. This future aligns with the timeless preamble of the Outer Space Treaty, a future that recognizes the deep connection between human civilization and our only Moon.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. UN, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty).
2. Outer Space Treaty.
3. Forbes, "Robotic Servicing of Geosynchronous Satellites (RSGS)"; and DARPA, "Consortium for Execution of Rendezvous and Servicing Operations (CONFERS)."
4. CONFERS: Fostering the Satellite Servicing Industry, https://satelliteconfers.org/.
5. Nayak, "10-Year Lunar Architecture Capability Study (LunA-10)."
6. DARPA, "Accelerating Interoperability Standards for Commercial Lunar Infrastructure."
7. NASA, "Moon to Mars Architecture."

3

DARPA's 10-Year Lunar Architecture (LunA-10)

Michael Nayak

Dr. Michael Nayak, call sign Orbit, has been a Program Manager with DARPA's Strategic Technology Office and the Defense Sciences Office. He conceived of and ran the 10-Year Lunar Architecture (LunA-10) study. At DARPA, he also founded and ran programs in the areas of astrophysics, parachute flight, high-energy physics, atmospheric science, space control, and quantum information science. He is a planetary scientist, US Air Force Test Pilot School graduate, aerospace engineer, and published science fiction author. He has flown an X-plane, worked flight test for the prototype T-7A jet, and deployed to the South Pole as a US Antarctic Program Principal Investigator.

It is the year 2035, and a thriving lunar economy exists on the Moon. How did we get there?

This is the first line of DARPA-EA-23-02, an Exploration Announcement from the Defense Advanced Research Projects Agency (DARPA) announcing open solicitations to the 10-Year Lunar Architecture (LunA-10) Capability Study.[1] Phrased another way: it's 2025 today, and the clock is ticking. How *do* we get there?

3.1 A Historical Note

From October 29 to 31, 1984, a NASA-sponsored, public symposium entitled "Lunar Bases and Space Activities of the 21st Century" was hosted by the National Academy of Sciences in Washington, DC. Approximately 300 attendees registered to hear 135 papers on a variety of topics relevant to space program goals in the era following establishment of the [International Space Station]. Since very little research on these issues is currently being funded, the many participants who traveled to the meeting tended to have a very personal, as well as professional, interest in the theme.[2]

So begins chapter 1 of *Lunar Bases and Activities of the 21st Century*, a collection of short papers dealing with various aspects of a crewed lunar base, and the "concomitant expansion of humanity into near-Earth space."[3] This compilation, edited by W. W. Mendell and published by the Lunar and Planetary Institute, stands as a snapshot in time—the state of science, politics, and space—right after America ended its last quest for the Moon. Most attendees had been a part of the towering accomplishments of the Apollo program, but the reality of this era-defining program ending was already sinking in.

Forty years later, America is going back to the Moon. As we embark upon this journey, trying to create a different outcome than in the 1970s, there are valuable lessons learned buried in the pages of Mendell's snapshot in time. These lessons, among others, informed how DARPA crafted its seminal LunA-10 study. It is my hope that the lessons of LunA-10 and the snapshot in time captured within this *Field Guide* can provide as much perspective to a future space architect as Mendell and his cohort of dreamers did to me.

3.2 The Role of DARPA

DARPA is a strange place.

Perhaps that is unsurprising. The agency's chartered mission is to change what's possible; sometimes, that means thinking about a challenge from a completely different angle. Above all else: DARPA employs and funds technological innovators. Program Manager C. David Lewis once said, "When you're here at DARPA you get to sort of divine into what the future can be, and then you grab that future and try and drag it to the present."[4]

DARPA created the first networked computers, which grew into the sprawling web of the internet. It created the first miniaturized position navigation and timing devices, and today, GPS is used for everything from navigation on phones to timing signals in ATM machines. It funded mRNA research, and today the world has used mRNA vaccines to move past a global pandemic.

There's a theme to those examples: DARPA did the early, targeted, foundational development of a scalable node. Those nodes were then expanded by someone else and grew into something that underlies the fabric of modern life.

Walking through the door of the agency's headquarters, you feel that legacy. A saying at DARPA goes: If you don't invent the internet when you come to DARPA, the best grade you get is a "B." But being a DARPA PM means you don't really pay attention to all that. It's already history. The job of a DARPA PM is to make the future. Imagine it, craft it, then drag it into the present.

And that's what makes DARPA such a strange place. It's not just believing in a future that doesn't exist. It's finding the specific technical insight to create that future. Knowing "when the time is right" for a particular innovation to make an asymmetrically large difference.

That's why the Moon, today.

America was done going to the Moon before I was born. But the Apollo program spawned a generation of dreamers, and we learned how to catapult humans out of our own gravity well safely and repeatedly. Suddenly it wasn't just governments that could launch into space, but companies. Not just large companies, but small start-ups. Not just low Earth orbit, but deeper into space. A new technological revolution is on the horizon: commercial discovery and exploitation of the Moon.

For the first time ever, an off-Earth economy is a possibility.

Just as DARPA seeded the key node of terrestrial utilities like the internet, GPS, Siri, and moving maps, the LunA-10 Capability Study aimed to find out if DARPA had a role to play in doing the same for the Moon. Launched in 2023 and completed in 2024, LunA-10 asked how we might seed utilities and civil services and galvanize the setup of a future civil and commercial infrastructure for the Moon. The "10" in LunA-10 stands for ten years from today, approximately 2035.

DARPA is a catalyst agent. A key part of why the agency has been so successful is that it aims for a key breakthrough—and then *leaves*. This is how DARPA approached the problem of going back to the Moon. For the US government, it will always be the National Aeronautics and Space Administration (NASA) leading America's efforts to go, land, live, and explore on the Moon. DARPA, however, can consider new approaches to the problem. It can take risks on behalf of the government that no one else can take. So, what can DARPA do to take significant risk, demonstrate an acceleration in the art of the possible for the Moon, and then get out of the way for an enduring partner to make the remainder of the investment for *shared prosperity at speed and scale*?

Answering that question is why LunA-10 was created.

While DARPA's traditional purview has been programs in support of national security, as America and its allies return to the Moon, DARPA aims to support NASA to develop technology purely for civil applications, including use by NASA on the surface of the Moon. DARPA supports a future model where NASA, international governments, and commercial industry can rapidly scale up lunar exploration and commerce, enabled and supported by the deployment of an efficiently combined, *integrated lunar infrastructure framework*. A framework for integrated lunar infrastructure would upend the current technical paradigm, where each lunar activity must organically support all resources it needs, such as its own survival power, data storage, and communications. At a million dollars per kilogram, that becomes a high barrier to entry.[5]

This sets the future that LunA-10 hopes to ultimately incentivize: a move away from individual scientific efforts within isolated, self-sufficient systems and toward a series of shareable, scalable, sustainable, resource-driven systems that can operate jointly. This would reduce the barrier to entry and create monetizable services that may be offered to future lunar users.

One way to do that may be a "Swiss army knife" type of solution. Today, Company X is building a comms puck. But under LunA-10, that puck could also become a positioning, navigation, and timing (PNT) beacon for GPS that runs on wireless power, be robotically assembled, and also be an edge processing node. Several examples of this *multiservice concept* are discussed in this *Field Guide*.

LunA-10 studied several business and technical cases for technology concepts designed into shareable, scalable, and resource-driven systems. It focused on creating monetizable services for future lunar users in a mass-efficient manner, while complementing existing NASA and international partner investments. Analytical frameworks for the future lunar economy created by LunA-10 and presented in this *Field Guide* are intended for future use by the United States and all nations with a declared commitment to the peaceful use of the Moon per the Artemis Accords.[6]

Today, commercial industry is moving fast. The rapid expansion of "new space" has revolutionized ways to deliver mass and capability to the Moon. The IM-1 mission from Intuitive Machines (2024) was the first in a continuing series of innovative commercial attempts to land on the Moon. In 2030–2035, commercial heavy-lift vehicles like New Glenn, Starship, and Vulcan are projected to begin delivering 10 to 100 metric tons of payload per landing on the Moon. These capabilities, and new commercial vendors, can create real off-Earth industry that can change the way we think about the Moon.

3.3 The LunA-10 Cohort

To get to a thriving lunar economy by 2035, three things need to be understood:

1. How to push from individual self-service (Exploration Age) to an era of commercial multiservice (Industrial Age).
2. How to push from government as a sponsor to commercial industry as a customer.
3. For a given lunar commercial service: What are the inputs, outputs, and limitations?

In the Fall of 2023, at the Lunar Surface Innovation Consortium in Pittsburgh, DARPA unveiled its consortium of LunA-10 companies, ranging across big and small, US and international, government and venture funded. The companies were organized into five key services that could feasibly be monetized over the next ten years: (1) power (Blue Origin, Fibertek Inc., Honeybee Robotics); (2) mining and in situ resource utilization (ISRU) (CisLunar Industries, Helios, Sierra Space); (3) construction and robotics (GITAI, ICON); (4) transportation and logistics (Northrup Grumman, SpaceX); and (5) communications, positioning, navigation, and timing (Crescent, Fibertek, Redwire), all underlined by early market analysis (Firefly Aerospace).

This portfolio of "performers," as exemplars of the lunar community, worked together to frame specific examples of what government and commercial industry could do to bring about a thriving, self-sustaining lunar economy. A baseline framework was created to calculate, to the gram, the watt, and the dollar, what a lunar economy could look like by 2035. Part 2 of this work discusses technical details broken down by commercial service, ultimately coalescing into an analytical framework and series of discrete value chains for further economic analysis.

This is not *the* answer to what the lunar future will look like. But it is *an* answer, from which the lunar community can move forward with specificity. Implicit in this answer are numbers that make a difference: critical masses to make the lunar economy self-perpetuating.

In February 2024, DARPA organized the "LunA-10 Enablers Workshop" in Arlington, Virginia. This workshop sought out perspectives that were not engineering-based but would be pivotal to a successful lunar economy. A few examples are space insurance, space law, economic and financial analysis, venture capital, and space policy. What were technical engineers and lunar scientists not thinking of as they planned out a future economy? Perspectives from those critical "Enablers" are captured in part 3 of this work.

Finally, in the spring of 2024, DARPA returned to the Lunar Surface Innovation Consortium, this time at the Johns Hopkins Applied Physics Laboratory (JHU/APL) in Laurel, Maryland. There, both commercial companies and DARPA presented the results of their findings to the broader lunar community, summarizing over 28,000 person-hours of work to conceptualize and technically anchor a future, interconnected lunar economy. Teams solicited feedback from the community on what was missing. This *Field Guide* represents the final product from all these interactions.

Commercial ventures, particularly small businesses, live and die by fundraising cycles. How does a company working on lunar technology, with twenty-four months of funded runway, show revenue for a Series A valuation without going to the Moon? This suggests that time is the equation that matters in the commercial economy. Economic prosperity only comes with speed. Revenue only comes with scale. LunA-10 was therefore aimed at answering key questions of *shared prosperity at speed and scale* on the Moon. Not just NASA, but all of government. Not just government, but commercial. Not just America, but international.

3.4 *Field Guide* Summary, with Our Surprising Findings

This *Field Guide* captures work done to define technological products and commercial services for the future lunar economy conducted under DARPA's LunA-10 Capability Study. This section summarizes some of the surprising findings that may not be common knowledge at the time of this writing. Additional details may be found in the chapters indicated.

Chapter 4 discusses technical solutions for scalable, mass-efficient, lunar wireless power as a persistent utility. Any architecture dependent on "pack-in" power solutions will face difficulties in scaling up and expanding. Offboard power can unlock a paradigm with a different way of designing surface vehicles, particularly for surviving the long lunar night and prospecting within permanently shadowed craters. Orbit-to-surface space-based solar power is analyzed as an alternative. While scientifically feasible, it was not found to be commercially viable.

Chapter 5 focuses on two methods being actively developed for in situ resource utilization: molten regolith electrolysis and carbothermal reduction. Two conceptual designs for commercial minimum viable experiment systems are outlined, with their scaling to large-scale production on the Moon. A new insight is presented: heated, deoxygenated regolith (DOR), a waste product from lunar regolith oxygen extraction, is a viable commercial product for resale in a lunar economy. Its energy gap makes it difficult and unprofitable to be reheated later but makes it suitable for use in lunar environments that suffer from significant thermal fluctuations. Timely robotic delivery will be required to transport DOR from producer to user while it still contains most of its heat. In general, LunA-10 found that waste from one lunar asset may be useful in a transformed state to another asset and thereby monetizable for secondary income.

Chapter 6 discusses a new concept: a commercial metal ecosystem on the Moon. This can, of course, be metal extraction from native lunar regolith. But once a lunar lander is defunct and out of power, it becomes part of the in situ environment. This is particularly relevant to the current generation of landers that are not night survivable. These vehicles contain a large quantity of aerospace-grade metals and carbon, which is not native to the lunar surface. This chapter posits the new concept of "Re-ISRU," or recycled in situ resource utilization, shows that recycled metals can be monetized, and defines a new lunar value chain.

Chapter 7 visits communications and lunar PNT. One example of a multiservice node is presented, which is capable of scalable configurations that sell communications to Earth, surface area networking, space traffic management, PNT signals, and the ability to survive the lunar night in one commercial unit. Optical communications from and around the Moon are also discussed.

Chapter 8 introduces "Robotics as a Service" as a fundamental enabler to the construction and maintenance of a lunar economy, with a labor pay-per-use model. To bootstrap lunar infrastructure and not constantly pay to resupply new units from Earth, designing future lunar factories or vehicles to be compatible with robotic maintenance, unpacking, and assembly provides significant advantages. Three new use cases for Robotics as a Service are discussed.

Chapter 9 discusses the creation of commercial landing pads on the Moon for heavy landers. The concept of "lunar fixed base operators" is one with parallels to modern-day aviation, especially when coupled with other services. Such landing pads can be created entirely from in situ material, and production rates specific to laser vitreous multi-material transformation (VMX) are discussed. Using laser VMX to pave roads and landing pads maximizes the resource-efficient inputs of raw regolith, but a critical link exists between construction and wireless power.

Chapter 10 begins a discussion of lunar infrastructure hubs at which multiple commercial lunar services may be hosted. In an analogous manner to how river ports turned into major cities due to growing infrastructure, aggregation on the Moon at such cornerstone hubs may facilitate the fusing and co-optimization of several infrastructure sectors into standard payloads that can be delivered to the lunar surface. A design for one such scalable tower, up to heights well exceeding that of the Statue of Liberty, is presented. At key locations such as peaks of eternal sunlight at the lunar south pole, these towers can significantly increase solar illumination and relieve survive-the-night mass burdens.

In chapter 11, this infrastructure hub concept is expanded to discuss a new commercial service: consolidated thermal. Today, each user brings its own custom thermal management system, sized to radiate a maximum daytime heat load and provide heating to survive the night. Thermal hubs shift the burden of heat management away from the individual users to establish a more efficient local thermal microgrid. This is analogous to building tenants on Earth shifting away from individual furnaces and fans to a central HVAC system. This paradigm offers significant mass savings. By aggregating numerous users with variable demands, the hub can more efficiently be designed to the average demand rather than the sum of peak demands. Two designs for thermal hubs are presented; these can recycle rejected waste heat to heat cold users, reducing electrical power consumption.

Chapter 12 discusses the lifeblood of any economy: logistics and distribution. For commercial companies, time is revenue. A single lunar terrain vehicle (LTV)-class rover will take 133 trips and thousands of hours to move a single heavy lander's cargo from point of delivery to the point of need. There is a need for enhanced transportation and connectivity as the lunar economy begins to scale up, which can be met by a lunar railroad system, the design and scaling of which is discussed here.

Chapter 13 expands the idea of surface infrastructure hubs to the orbital arena, via cislunar supply hubs. An in-space harbor can be a central hub of infrastructure for lunar and deep space exploration missions and create a new paradigm: moving away from satellite end of life toward a symbiotic satellite "retirement." When rocket stages or spacecraft arrive with some fuel, data, communications, edge compute, or solar power, those can be repurposed as sharable resources that can be used across a hub in a harbormaster model. Arriving spacecraft would plug into the harbor and aggregate these resources. The capacity and functionality of the aggregation grows with every docked spacecraft, and every docked spacecraft has the potential to become the nucleation point for a new harbor or service destination.

Chapters 14 and 15 stitch these disparate commercial services into a cohesive unified framework: a vision for a future possible with today's technology. Four distinctive stages of development are identified: The Exploration Age, the Foundational Age, the Industrial Age, and the Jet Age.

Part 3, "Beyond the Technology: Enabling Perspectives," kicks off with a discussion of enablers and inhibiters to the LunA-10 framework from space treaties and international law (chapter 16). Chapter 17 explores responsible economics for lunar exploration and market growth, discussing specific financial design principles, market transparency, governance issues, and specific recommendations for each of the four lunar ages. Chapter 18 discusses a self-governing rules-based framework created independent of governments. This chapter posits that the international community is unlikely to develop an adequate rules-based framework on its own; a Lunar Development Cooperative could address this dilemma by serving as the framework for deploying and managing future lunar infrastructure, financed and directed by commercial space users and investors.

Chapter 19 uses US Antarctic Program operations as a case study to investigate how lessons learned from Antarctica may apply to logistical, operational, and legal challenges on the Moon. Lessons learned from air traffic control operations in Antarctica may guide future lunar framework designers in how to ensure a cooperative, international, and interoperable future.

Chapter 20 discusses biomanufacturing in space and on the lunar surface, addressing technologies that directly support a human presence on the Moon. Mission-critical inventories of de novo synthesized components of food, pharmaceuticals, and materials will be critical to a future where humans are part of a thriving lunar ecosystem.

Chapter 21 discusses, for the first time, the unique role that space insurance may play in commercialization of the Moon. Current forecasts are not encouraging: in 2023, insurance companies operating in space experienced losses that surpassed the total premiums collected. Premiums for lunar surface missions could be an order of magnitude higher than those for orbital missions, which would severely impair the growth potential of a lunar economy. Risk factors and potential solutions to consider early are summarized.

The creation of standards for lunar interoperability will enable a new sector of the lunar economy, promote the creation of new business and jobs, and allow new companies to rapidly join and interface with legacy lunar players and existing infrastructure. Decisions being made now will influence the development of interoperable foundational technologies that underlie a robust lunar economy. Chapter 22 discusses the DARPA-funded international consortium that addresses this challenge: the Lunar Operating Guidelines for Infrastructure Consortium (LOGIC).

America is going back to the Moon, and if we are truly going back to stay, it will require government agencies to partner with fast-moving commercial industry and international partners. LunA-10 represents one pin in a vast map, created by DARPA, in partnership with NASA, the US Geological Survey, and other government agencies. It spelled out the vision encompassed in the chapters of this *Field Guide*.

But to make it real?

That will take *you*.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. LunA-10 Exploration Announcement Solicitation, August 15, 2023, https://sam.gov/.
2. Mendell, *Lunar Bases and Space Activities of the 21st Century*, 5.
3. Mendell, 1.
4. C. David Lewis, "DARPA Program Managers," posted June 5, 2023, by DARPATV, https://www.youtube.com/.
5. Commercial estimate (Astrobotic Inc.) for payload to the surface of the Moon, current as of May 2024. See also Astrobotic.com, "Astrobotic Lunar Landers: Payload User's Guide," August 2021, https://www.astrobotic.com/.
6. The Artemis Accords describe a shared vision for principles, grounded in the Outer Space Treaty, to create a safe and transparent environment that facilitates exploration, science, and commercial activities for all of humanity to enjoy. Details are available at NASA, "Artemis Accords," https://www.nasa.gov/.

PART 2

COMPONENTS OF COMMERCIAL LUNAR INFRASTRUCTURE

4

Lunar Power

Edited by Michael Nayak

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4.1 Introduction and Framing

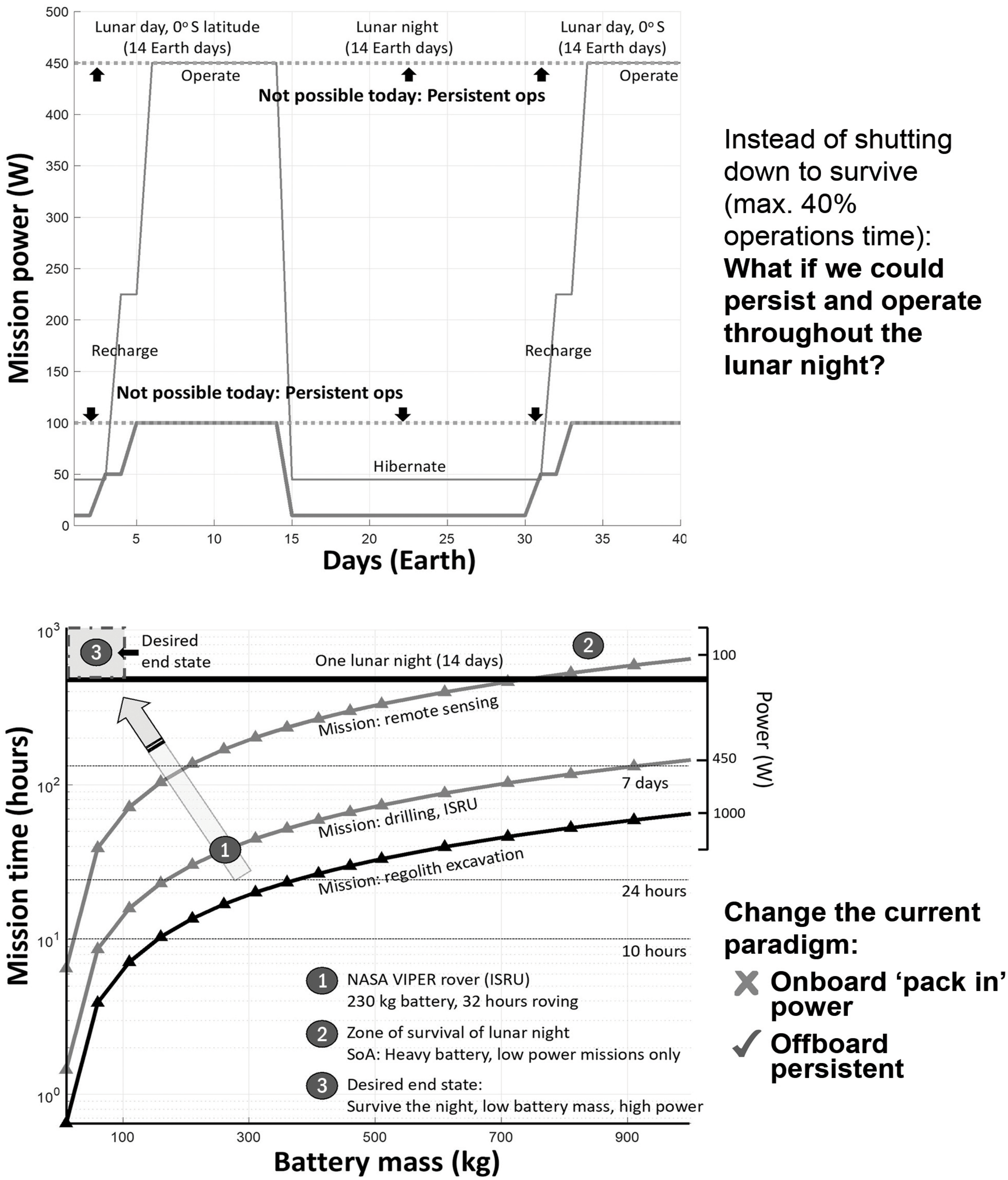
The plentiful availability of power is a critical enabler to the lunar economy. Most commercial lunar activities scale output with power—the more power available, the faster these activities can scale. Two examples are lunar mining and lunar construction. Greater kilowatt-hours (kWh) of power available directly translates into a greater mass of monetizable resources harvested (kg) or a larger diameter of landing pad constructed through sintering of the lunar regolith (meters). This is an example of a value chain, discussed further in chapter 15.

To enable a self-sustaining lunar economy, megawatt-hours (MWh) of power need to be available to lunar consumers. This enables dozens of landing pads and thousands of kilograms of mined resources. The current state of the art is self-contained power: each lunar unit brings its own power generation capability, through solar arrays, radioisotope thermoelectric generators (RTG), or other means. This is a far cry from the state of the art on Earth, where any new service can simply plug into an existing grid to receive as much power as needed and pay on a per-unit (kWh) basis to scale up in operations.

On Earth, due to sustained infrastructure investment by private and public power companies, scalable *and* mass-efficient wired power is available as a persistent utility. For mobile applications, high energy-density fuels such as gasoline are available at thousands of locations in a given geographical area. Both gasoline, through gas stations, and electrical power, through a long-distance electrical grid, are *utilities* that a commercial user can depend on and make plans around. Power on the Moon that operates as a *persistent utility* directly enables the proliferation of commercial activity on the lunar surface. Therefore, it is the first component of commercial lunar infrastructure addressed in this *Field Guide*.

The big technical barrier to proliferated power on the Moon is surviving the long lunar night. At the mid-latitudes, night lasts fourteen continuous days. At the poles, in permanently shadowed regions (PSR), night lasts forever. A paradigm shift is needed to push commercial activities on the Moon toward persistent survival and operation, even in the most energy-deficient environments. The flash point for businesses is some combination of multiple supported users, high uptime of power available, and a statistically significant chance of having that power for a long time, i.e., the power utility surviving the harsh lunar environment. In other words: *scalable, mass-efficient, lunar wireless power as a persistent utility.*

Today's paradigm is far from this vision. Recent commercial lunar landers (e.g., Intuitive Machines IM-1) have returned the American flag to the Moon, but they cannot currently survive the lunar night. Even if they could hibernate to survive, such systems would operate at a maximum of 40 percent of the time (fig. 4.1). A commercial economy cannot thrive if it can only operate during sunlit hours.



Key
ISRU: in situ resource utilization
SoA: state of the art
VIPER: Volatiles Investigating Polar Exploration Rover

Figure 4.1. The current lunar power paradigm is limited by onboard energy. A shift toward an offboard persistent utility is needed to galvanize a future commercial lunar economy.

Figure 4.1 (bottom) shows three exemplar mission sets on the Moon, with different power levels: remote sensing, spot activity such as drilling or resource refinement, and large-scale activity like excavation. Today it is only possible to survive the long night at low power levels, with the expense of significant mass. Some mission sets are simply not possible persistently. This paradigm becomes even more limiting at PSRs, where the 50 percent sunlight available at the lunar equator can be as low as 0 percent sunlight.

In summary: any architecture dependent on "pack-in" solutions, such as today's lunar rovers, will face extreme difficulties in scaling up and expanding. Offboard power, however, can unlock a paradigm with a completely different way of designing surface vehicles. Through the enabling technology of power beaming, operating through the lunar night, at low battery masses (fig. 4.1, bottom, "desired end state") may be able to fill the technological white space of low mass and high power simultaneously. Later in this *Field Guide*, energy estimates for metal-based in situ resource utilization (ISRU) are developed, which provide insight into the significant power requirements of in situ resource production in general.

Section 4.2 discusses optical-wavelength power beaming, using one example of a scalable commercial unit to illustrate the applications possible. Section 4.3 discusses space-to-surface radio frequency (RF)-wavelength power beaming and its commercial feasibility. Section 4.4 discusses regenerative fuel cell energy storage. Section 4.5 discusses wired power on the lunar surface. Section 4.6 summarizes other lunar power modalities not explored in this work.

4.2 Optical-Wavelength Wireless Power Transmission (OWPT)

4.2.1 Introduction to OWPT

For offboard power transmission, aperture size scales with wavelength across the electromagnetic spectrum, including radio, microwave, and optical frequencies. Therefore, by nature, optical-wavelength power transmission will tend to be the most mass-efficient as it is the shortest wavelength and therefore requires the smallest physical apertures. In contrast, RF power transfer requires aperture sizes in the tens of meters to scale up to meaningful amounts of power (MWh). This is evaluated further in section 4.3.

Long-distance, laser-based optical wireless power transfer is rapidly emerging as a new modality for transferring power. OWPT is attractive for the lunar surface because: (1) it can transmit power over long distances without the mass of conductive wires, (2) it can power mobile assets that would otherwise be mass- and range-constrained, and (3) it can flexibly redistribute power between different assets over a large service area as power distribution needs change over time.[11] An example use case for OWPT is a commercial unit that gathers solar power on the rim of a crater, converts it into optical energy, and transmits that energy via a laser to a rover traversing a permanently shadowed crater, thereby extending its lifetime and range while reducing its mass. However, a drawback of OWPT is that the end-to-end efficiency of transmitted power, in terms of total electricity transferred, is relatively low.

Free space or wireless power beaming uses electric power from an existing source and converts that electricity into high-intensity light using a laser. Optics in the transmitter shape and transmit this invisible beam of light to a designated receiver, where light-absorbing photovoltaic cells convert the light into electricity. The system includes end-to-end safety hardware and software that manage reflected and misdirected light, proximity incursions, beam intrusions, and system malfunctions. This is part of the control system that commands subsystems and performance while enabling remote data telemetry for monitoring.

An OWPT system needs to be engineered to meet mission requirements: that is, transfer a minimum amount of electrical power (measured after the receiver) up to a maximum range and within a given size, weight, and power (SWaP) budget. On the transmitter side, laser output power can be controlled by the laser itself, and the laser spot size at the receiver can be controlled by the diameter of the transmitter telescope optics. On the receiver side, the area of the receiver should be matched to the laser spot size for maximum efficiency, and the maximum allowed incident laser power is limited by the receiver efficiency and thermal rejection capacity because most incident laser power that is not converted into electricity is converted into heat at the receiver.

A commercial OWPT unit can provide multiple infrastructure services to a lunar economy. This is centered in laser-based power to a surface-based user but could also include a bidirectional laser-based communications backbone and time transfer, enabled by an optical communications link to Earth, for positioning, navigation, and timing (PNT) and clock distribution.

4.2.2 Benefits of OWPT

Laser power beaming provides flexibility of location for power-using devices. A lunar user can be mobile and still receive power if it has a line of sight to the transmitter. In many situations, power beaming can deliver power where running a cable would be prohibitively expensive, slow, or dangerous. OWPT thereby offers unique advantages for lunar exploration and resource utilization:

- Enhanced rover productivity. OWPT can eliminate downtime during solar charging and reduce energy spent traveling to and from charging stations. A rapid pointing and acquisition capability allows sequential charging of spatially distributed users with minimal downtime between charges. Twenty to forty user charges per day can be provided at ranges up to 20 km. This number varies with user charge rate assumptions and total power required.
- Emergency remote power. OWPT can provide emergency remote power during equipment failures, mobility issues, or astronaut safety needs. The ability to charge batteries remotely can mitigate cold-induced battery drain, allowing mobile vehicles or outposts time for recovery and anomaly resolution. Emergency power can be provided at long ranges (survival power levels can reach well beyond 20 km) and be distributed dynamically at the speed of light.
- Permanently shadowed region (PSR) exploration. OWPT facilitates exploration of PSRs by supporting mining and hauling operations. It can power remote charging stations for hauler vehicles or permanently stationed ISRU plants.
- Transient surface operations. OWPT serves as a low-mass solution for extended missions, offering sustained power infrastructure without the logistical and resource overhead of transporting a tether cable, solar, fission surface power (FSP), or power generating mass. This reduces logistics and equipment needs for prospecting and mining.

Scalable Commercial OWPT units can be integrated in several ways, such as

- with infrastructure-node towers distributed across the lunar surface (see section 4.2.5 for more detail on tower configurations)
- with low lunar orbit (LLO) spacecraft for orbit-to-surface OWPT and optical communications;
- with lunar landers of all sizes, to power offloaded rovers or other delivered units such as ISRU plants; and
- with other power generation sources for wireless transmission of that power, such as solar farms, FSP units, or fuel cell power sources for nighttime operation.

4.2.3 System Overview and Scalability

Modular by design, OWPT can be scaled from an initial surface technical demonstration to validate the technology to a full lunar surface power distribution and communications infrastructure. The near-diffraction-limited beam propagation of ytterbium (Yb) fiber laser technology enables OWPT over 20+ km range with compact, 15 cm beam director optics and a <50 cm diameter receiver. Yb fiber amplifiers can convert ~85 percent of the laser diode optical power into 1.064 µm light. This makes a laser approach competitive, from an optical efficiency perspective, with direct laser diode technology used in the 900 nm region, such as that used on the NASA Moonbeam program.[12] Direct laser diodes, however, are typically 20 to 60 times poorer quality than diffraction-limited beams, which limits their range of operation.

To root a discussion of OWPT scalability in technical detail, the Lunar Infrastructure Optical Node (LION) product from Fibertek, developed under LunA-10, is discussed as a representative example. LION leverages high Technology Readiness Level (TRL) maturity and heritage from space laser and optical communications technology, including a NASA-funded Artemis optical communications terminal.[13] It can input power from solar panels or a surface fission power (SFP) generator and then wirelessly distribute it to users.

The LION terminal is modular and scalable to a variety of configurations suitable for different lunar platforms. Five viable products have been identified as part of LunA-10 (fig. 4.3). The full-size LION can supply 5.9 kW, LION Mini can supply 3.0 kW, LION Micro 740 W, and the LION Nano 350 W of regulated power to users.[14] The fifth, LION Multi, is comparable to the full-size LION but was developed with beam directors to scale power transmission to multiple users simultaneously. Power transfer efficiency estimates range from ~18 percent to 26 percent with further technology development.

In general, modularity for OWPT involves using the same core technologies across a commercial product line, including lasers, optics, and short- and long-range laser communications terminals. This provides significant benefits from a nonrecurring engineering perspective. For example, LION terminals (fig. 4.2) scale OWPT power by increasing the number of lasers, with all terminals designed to charge moving vehicles, and support multiple users simultaneously, while providing optical communications as an additional service (see section 7.4 for additional details).

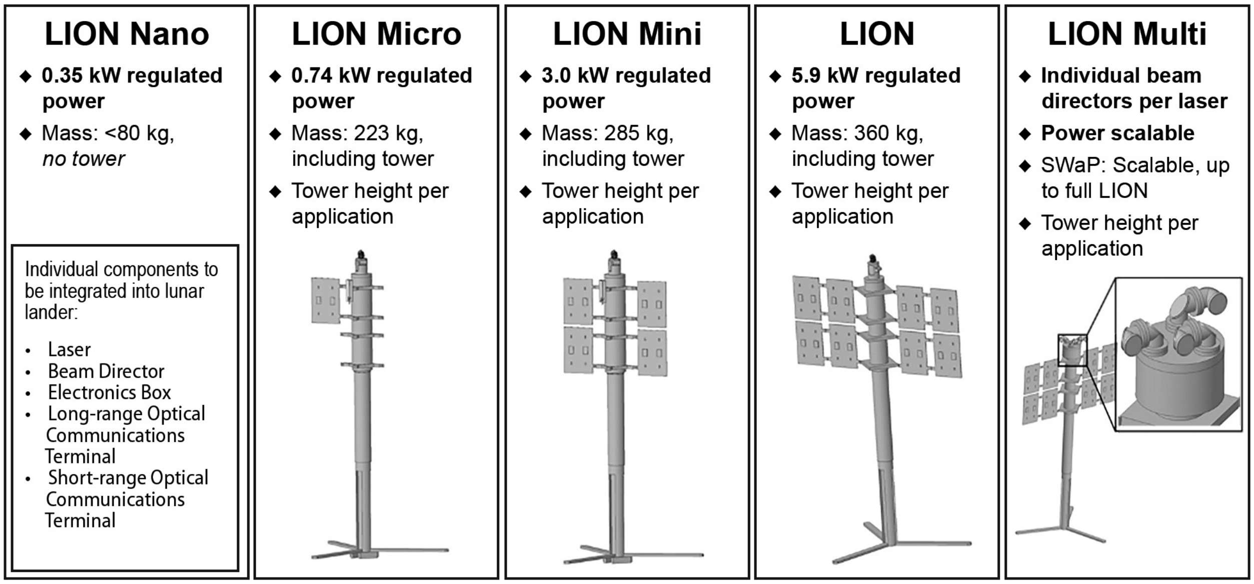


Figure 4.2. LION family of scalable OWPT configurations using a common core subsystem. [Credit: Fibertek]

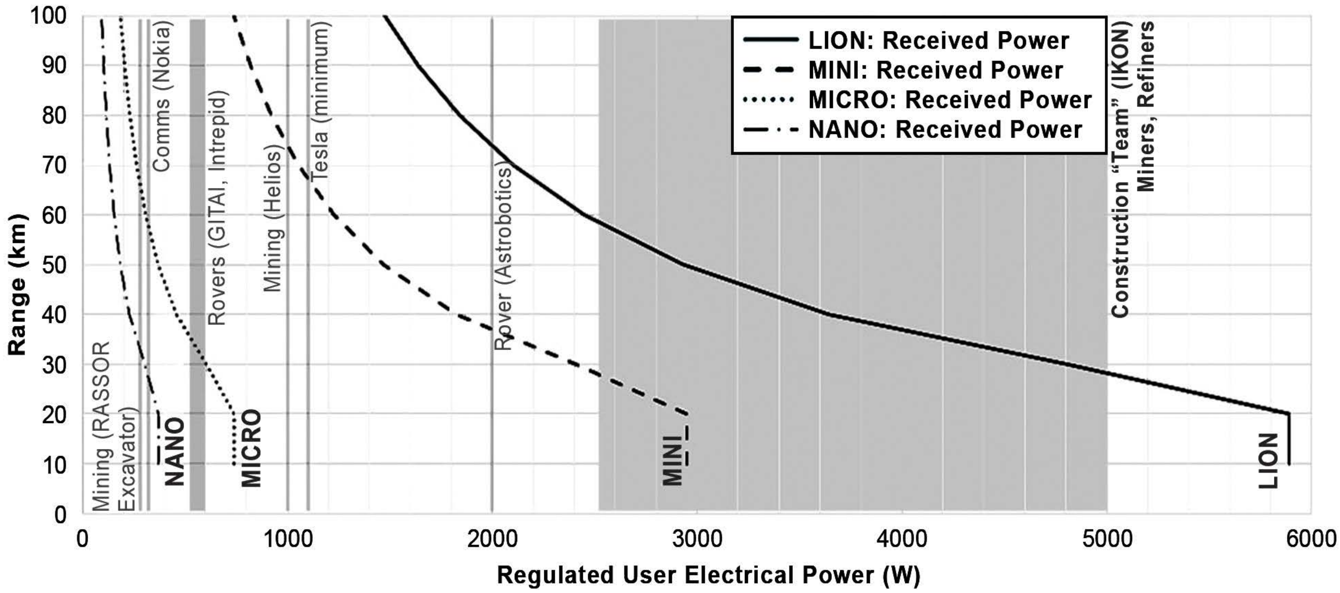


Figure 4.3. Range vs. maximum regulated electrical power provided to the user for LION Full, Mini, Micro, and Nano. Various surface capabilities and corresponding power requirements are overlaid. [Credit: Fibertek]

Figure 4.3 overlays applications, indicated by vertical lines against the maximum regulated electrical power provided, for various scaled units. It can be seen that:

- OWPT is optimized for long-range high-power transfer using high-TRL technology;
- during the LunA-10 program, Fibertek surveyed potential lunar power customers to generate an estimate of the peak charging power and rates by customer applications. This survey showed that most lunar surface operations require <1 kW peak electrical power to recharge batteries over short durations;
- mining, refining, construction, and PSR operations require ~2 to 5 kW power;

- OWPT can charge vehicles in motion. Charging time is commensurate with vehicle charge rates and capacity; and
- the power provided by an OWPT unit begins to decrease beyond 20 km as the laser beam spot size expands beyond the Laser Power Conversion (LPC) receiver area but still provides critical power capabilities to 100+ km as long as line of sight is maintained.

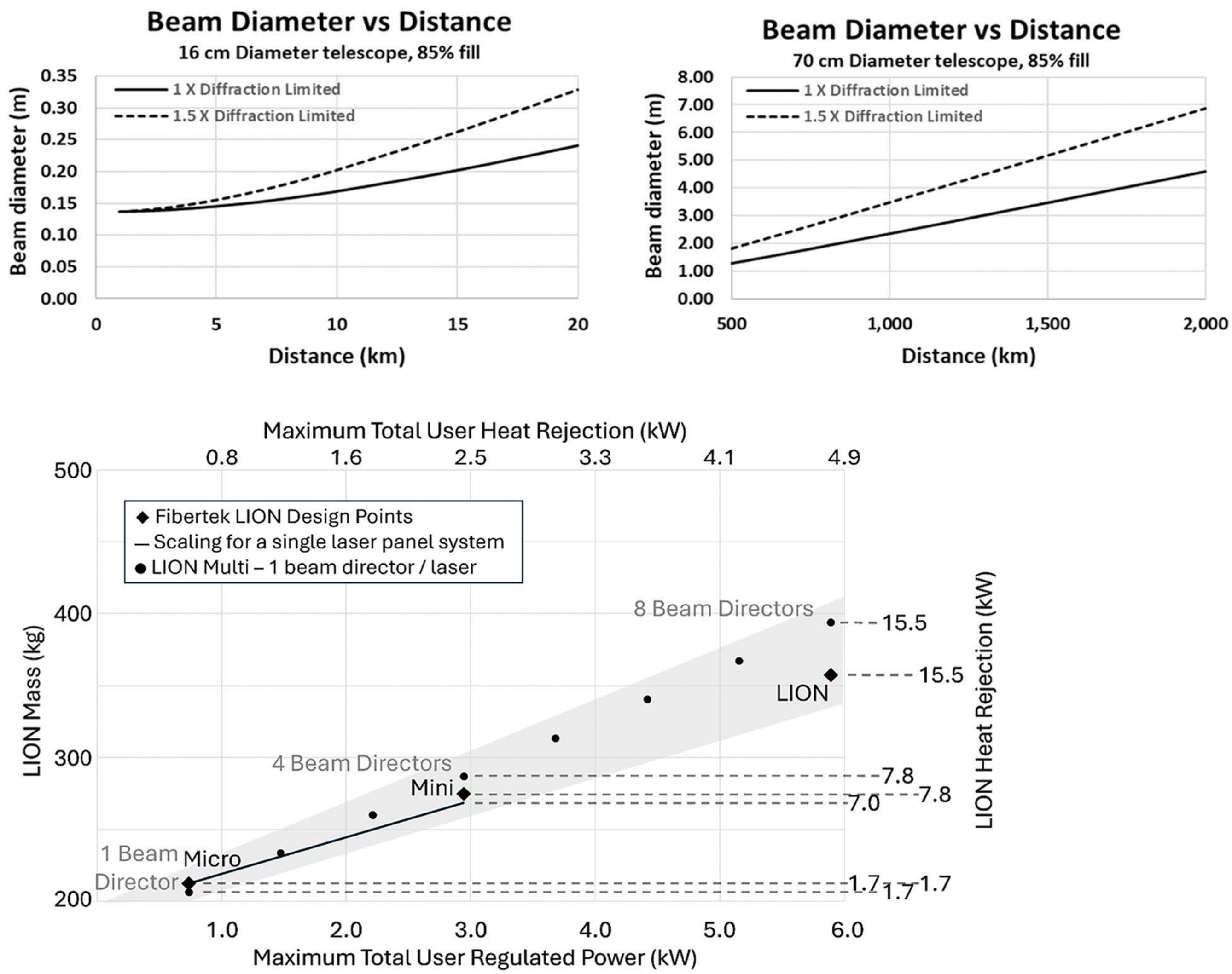


Figure 4.4. (Upper left) Laser beam diameter vs. range assuming a 16 cm telescope. (Upper right) Laser beam size vs. range for a 70 cm telescope in low lunar orbit (LLO) to the lunar surface. (Lower panel) LION mass vs. maximum total user regulated power and heat rejection for a range of LION terminals. The scaling of a single laser LION terminal is also shown. [Credit: Fibertek]

Figure 4.4 (upper left panel) presents the beam diameter of a near diffraction-limited Yb fiber laser versus range for a 16 cm telescope, assuming both a 1.0x and 1.5x diffraction-limited beam. The beam size expands to ~30 cm diameter over 20 km, still a reasonable size for a mobile LPC receiver. The same Yb laser can power a beam from a low lunar orbit (LLO) to the lunar surface as shown in figure 4.4 (upper right panel). In this case, a 70 cm telescope is assumed. The spot size on the lunar surface is <7 meters in diameter from a 1,500 km altitude orbit.

At differing scales, different OWPT terminals will have varying masses and thermal loads. An in-depth analysis of the mass and thermal implications was conducted including assessing the impact of employing multiple beam directors. Figure 4.4 (lower panel) shows all configurations analyzed. Most scale linearly, as expected, resulting from the modular adding of additional OWPT laser sources. An independent beam director for each laser bears a ~15 percent mass penalty. User heat rejection is seen to be only a function of maximum total user regulated power, and OWPT heat rejection is near-linear as a function of unit mass.

As an example of an OWPT minimum viable experiment (MVE) for commercial lunar landers, the LION Nano was designed. The Nano differs from larger terminals in that each component is provided as a low SWaP subsystem. Similar MVE units from other providers can be integrated with a host platform nearly independently. This <80 kg and <2 kW input power configuration is designed for use on small commercial landers currently in development, thereby accelerating lunar surface demonstration opportunities. The system can provide 350 W of regulated power to a customer vehicle (for example, an Intuitive Machines Odysseus lander) and short- and long-range communications.

4.2.4 Commercialization of OWPT

As demonstrated by the example of the LION unit, OWPT infrastructure is generally scalable, allowing for nodes of various capabilities to be distributed across the lunar surface. The prices for supplying services, however, are defined by capital costs, to include hardware, launch cost to the lunar surface, and operating costs, which include the cost of generating input power.

In fact, the price of input power on the lunar surface represents the biggest unknown to the price of OWPT services. Using price ranges of lunar surface power from the LunA-10 program, estimated prices for services have been calculated, based on one OWPT terminal operating at a 90 percent daytime duty cycle, 20 percent end-to-end efficiency, a cost to land on the lunar surface of $500,000/kg, and a commercial unit positioned at the south pole at a height of >100 meters, to limit the duration of local night (see section 4.2.5 for more details). Additionally, a ten-year mission duration and a tenfold price increase over daytime power for nighttime survival power were assumed.

The current best estimate for daytime lunar surface input power emerges on the order of $100/kWh, three orders of magnitude more expensive than terrestrial electrical power ($0.10/kWh). The fully loaded production price for lunar power beaming is between $1,400 and $1,800/kWh; capital costs, driven by the cost to land the LION payload on the lunar surface, are responsible for ~$1,500/kWh. This will need to be amortized over the duration of the power service (approximately ten years).

Because OWPT terminals operate independently, there is no inherent cost benefit with scaling the size of the infrastructure. Cost benefits, however, can be achieved by production at scale. This will reduce the unit price of a single node while benefiting from the inherent modularity to scale any individual node to meet local requirements at a high duty cycle. Such a concept supports a uniform service price across the lunar surface, as a function of local power input cost.

4.2.5 Increasing OWPT Visibility with Elevation

While OWPT can provide several benefits, it is fundamentally limited by line of sight. **A key insight from LunA-10 is: Increasing line of sight directly increases the area that can be serviced by OWPT and thereby increases commercialization potential by increasing the number of accessible users**. For a given tower height (h) and radius of Moon (r_m), the horizon distance (d_h) can be computed for a perfect sphere with no local topography. The theoretical horizon distance for a given height is given as:

$$d_h = \sqrt{(r_m + h)^2 - r_m^{\,2}}$$

Although this ideal sphere calculation ignores innate lunar surface topography, it can be used as a figure of merit. Using digital elevation models, the local horizon elevation angle can be computed to evaluate the line of sight to horizon at various heights of lander-hosted towers. This leads to the concept of *viewsheds.*

A viewshed is the local surface area visible from an observer's viewpoint. Viewshed analysis determines if a point on the Moon is visible from the top of a tower, to understand the service range of an OWPT unit hosted atop the tower. Due to the lunar topography, the performance metric may not be line of sight but rather access into a maximal number of adjacent crater bottoms.

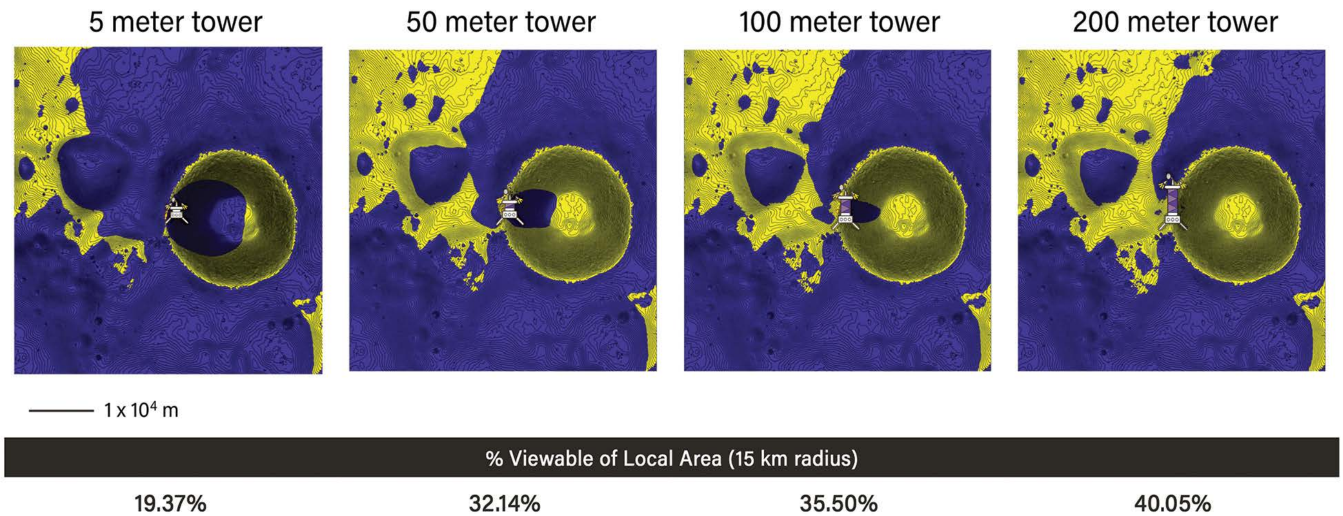


Figure 4.5. Viewshed for four selected heights of tower atop which an OWPT unit could be hosted. [Courtesy Honeybee Robotics]

The surrounding area viewshed for four selected heights of tower (5 m, 50 m, 100 m, 200 m) were analyzed (fig. 4.5). As the tower height increases, viewshed significantly increases. For example, an OWPT unit hosted atop a 200-meter tower could support a mobile user such as a rover anywhere within the Shackleton (south pole) crater, as well as across 40 percent of all surrounding terrain within 15 kilometers, regardless of user elevation. The feasibility of such a tower is discussed in chapter 10.

4.3 Space-Based Radio Frequency (RF) Power Transfer

Next, this *Field Guide* turns to a discussion of RF-based wireless power transfer. Given that a key design driver for OWPT is dependence on lunar day-night cycles, incorporating wireless power beaming from an orbiting asset may make it possible to eliminate time and other inefficiencies associated with surface-to-surface power transfer.

4.3.1 Introduction to Space-Based Solar Power (SBSP)

Space-based solar power systems collect solar energy in space and transmit it wirelessly to a user on the lunar surface. Some key considerations for RF-based wireless power beaming include the following:

- Solar energy collection. A key driver for SBSP is large, efficient solar arrays.
- Energy conversion. To convert solar energy into RF beams, DC-DC and DC-RF converters are required, which have losses and inefficiencies.
- Power beaming efficiency. Large distances and good coverage will highly affect end-to-end power beaming efficiency.
- Rectenna considerations. An effective rectenna will need to be fairly large, which comes with mass penalties.

- Orbital considerations. Beam collection and photovoltaic efficiency will vary with orbital position and dynamics.
- Thermal management. A large system utilizing RF wireless power beaming will need a robust system to offload significant amounts of waste heat.
- Economic viability. The cost of the system must be cost efficient against other forms of energy supply, such as nuclear (FSP) and OWPT.

4.3.2 Methods

RF power beaming performance is dependent on efficiency losses, according to:

$$P_{recieved} = P_{solar}\, \eta_{overall}$$
$$\eta_{overall} = \eta_{PV}\, \eta_{DC-DC}\, \eta_{DC-RF}\, \eta_{Antenna}\, \eta_{BeamCollection}\, \eta_{Rectenna}\, \eta_{DC-DC}$$

The key factors affecting efficiency for SBSP are the rectifier and beam collection efficiencies. Due to the long orbital distances between the transmit antenna and the rectifier, beam collection efficiency is the primary loss pathway. To model power beaming efficiency, Shinora's equations for beam efficiency of wireless power state the following:[15]

$$\tau^2 = \frac{A_r A_t}{(\lambda D)^2}$$
$$\eta_{BE} = \frac{P_r}{P_t} = 1 - e^{-\tau^2}$$

where λ is the wavelength, D is the separation distance, and A_r and A_t are receive and transmit areas respectively. Frequency selection has a significant impact on rectifier efficiency, with lower frequency systems typically having superior efficiency.

The assumptions in table 4.1 were used. For the LunA-10 program, an original concept to utilize a single phased array aperture for both synthetic aperture radar/moving target dentification (SAR/MTI) and SBSP was designed. This would create increased mass-efficiency and lower cost to create a commercial capability. Therefore, the operating frequency selection was based on the needs of a SAR/MTI architecture. An elliptical orbit of 100 x 6500 km was selected due to stability and lunar site coverage time, but distance and power delivered would vary across a lunar night.

Table 4.1. Initial space-based power beaming assumptions

Item	*Assumption*
Frequency	40 GHz
Orbits	Elliptical and highly elliptical
Transmitter antenna diameters	10m and 20m
Rectenna diameters	10m, 100m, and 1,000m
DC-DC converter efficiency	95%
Microwave converter efficiency	70%
Photovoltaic efficiency	35%
Rectenna efficiency	60% @ Ka-band
Visibility	10 degrees above horizon

Key
DC: direct current
Tx: transmitter

4.3.3 Results and Conclusions

Using the assumptions in table 4.1, the power delivered to a lunar surface user was calculated as a function of separation distance for a 20 meter transmitter system, with varying receiver diameters at 40 GHz (fig. 4.6, left). While a 1,000-m diameter rectenna is not feasible, the plot illustrates how sensitive the power delivered is to rectenna size.

As shown in figure 4.6, the orbiting satellite makes between five to six passes a day. With a rectenna 10 m in diameter, it is possible to collect up to 4 Wh per pass. This amount of energy is equivalent to charging a cellphone five times slower than normal. Orders of magnitude greater rectenna sizes (100 m and 1,000 m) yield correspondingly more power to the user (437 Wh and 43.7 kWh).

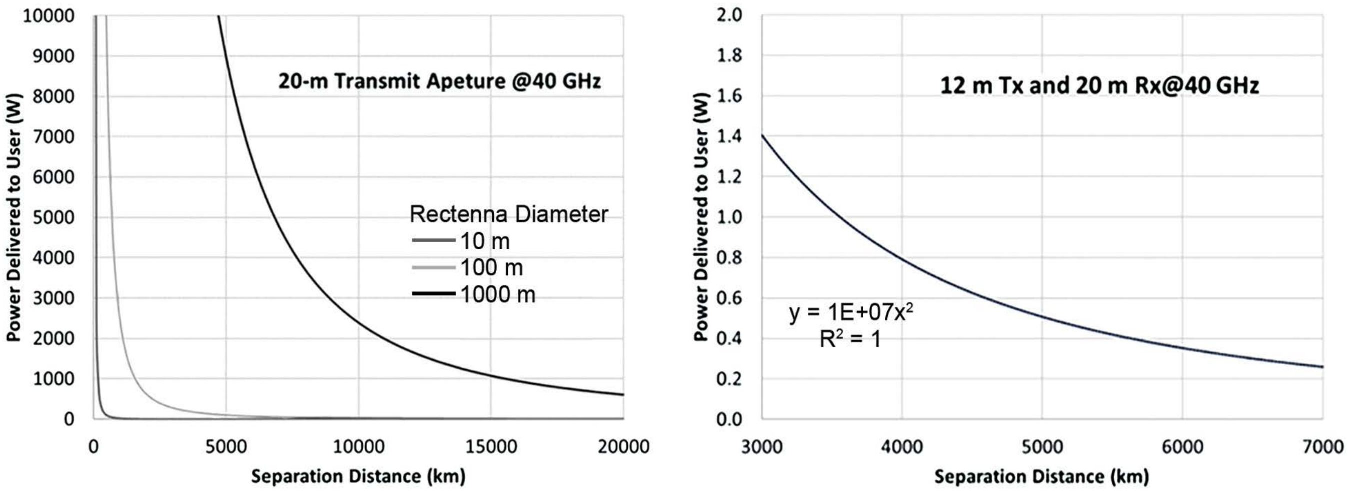


Figure 4.6. Power delivered via RF SBSP is highly sensitive to rectenna size. (Left) Power delivered at Ka-band to a ground-based lunar user as a function of separation distance and rectenna diameter. (Right) Power delivered to user over distance for 1 kWh analysis. [Credit: Redwire Space]

Changing the frequency band was not found to be favorable. By changing from Ka to X-band, an order of magnitude less energy was collected by the user (10-m rectenna, 0.4 Wh; 100-m rectenna, 43 Wh).

Next, orbit parameters were investigated. An elliptical 900 x 14,500 km orbit offered a balance between coverage and station-keeping requirements. Changes in distance and power with time were computed over a two-week period for a system with a 20 m transmit antenna and a 100 m diameter rectenna. Despite the huge apertures involved, this scheme would only deliver 40–80 Wh/day to a user.

Subsequent analysis looked at what it would take to get an appreciable amount of energy, specifically 1kW over a twenty-four-hour period, to a lunar user on the surface. Rectenna sizes of 12 m (transmit) and 20 m (receive) were used, from a 100 x 6500 km orbit, for 40 GHz frequency. All other assumptions were per table 4.1. The power delivered over distance for 1 kW received by the user is shown in figure 4.6 (right). A user could expect between 10 to 12Wh per Earth day from a single satellite, that is, ~100 satellites would be required to deliver 1 kW of continuous power to a user. Clearly, this is not a commercially feasible scenario.

A key finding from LunA-10 is that while orbit-to-surface RF power beaming is certainly feasible *technically*, the size, mass, and complexity of the required apertures do not suggest *commercial* viability.

4.4 Regenerative Fuel Cell Energy Storage

Regenerative fuel cell technologies have the potential to store energy more efficiently per unit mass than conventional Li-Ion battery systems. Current state-of-the-art Li-Ion batteries for space applications have a specific energy capability of 100 to 180-Watt electric (We) per hour per kg. Regenerative fuel cells are anticipated to have 600 to 1000 We-hr/kg capability. At 1 MWe-hr scale, a regenerative fuel cell energy storage system would save up to 4,500 kg of landed mass per mission compared to batteries.

A concept was explored to integrate multi-kilowatt H_2/O_2 proton exchange membrane (PEM) fuel cells into a scalable integrated electrical power system, to provide continuous power regardless of day or night lunar illumination conditions. For long-lived operation, solar array power production would be integrated with water electrolysis to regenerate H_2/O_2 from fuel cell product water. During the day, the system will produce and store H_2/O_2 in energy storage to be used for power production during the night.

The "regenerative" capability of the fuel cell is provided by water electrolysis. The power system takes stored fuel cell product water and converts the liquid H_2O to dry GH_2/GO_2 for storage in the reactant storage subsystem.

Water electrolysis technologies include polymer electrolyte electrolysis (PEME), alkaline electrolysis (AE), and solid oxide electrolysis (SOE) chemistries. Each chemistry has benefits and drawbacks depending on the application. The primary technical benefit of PEME is that the stack can be designed to seal and operate at very high pressures consistent with efficient GH_2/GO_2 storage. This is due to the solid state of the electrolyte and moderate temperature (<200°F) of operation. AE stacks (liquid electrolyte) and SOE stacks (~1500°F ceramics) generally operate at lower pressures. In space applications, AE performs at a slightly higher conversion efficiency than PEME but consumes electrical power for gas compression to efficiently store GH_2/GO_2. SOE has cost, complexity, and mass challenges due to its high-temperature operation, with few benefits over PEME or AE for water electrolysis.

4.5 Wired Power

Another method of power transmission on the Moon is to use wired conductors. While wired power comes with numerous logistical challenges, particularly for mobile users, it has relatively high transmission efficiency (>80 percent) for both the wire and any power conversion necessary for transmission over distance. Since the power loss is proportional to the square of the current, a typical wired transmission system uses a boost converter to increase voltage for transmission, then a buck converter at the receiving end to reduce voltage for the end user.

NASA is funding universal modular interface converter (UMIC) technology that offers bidirectional conversion to three-phase 3,000 volts alternating current.[16] Combining this with, for example, the Tether Power Systems for Lunar Surface Mobility and Power Transmission technology, developed by the Jet Propulsion Laboratory,[17] could provide a mass-efficient and robust wired power transmission solution. However, a true breakthrough in the weight paradigm for cabled power technology would occur if such cables could be manufactured from in situ resources on the Moon; the manufacture of wired power cables as a product of a metal foundry system is discussed further in chapter 6 of this *Field Guide*.

4.6 Not Discussed, and Why: Fission Surface Power

Nuclear fission surface power (FSP) is a unique way to rapidly grow the lunar economy. LunA-10 did not explore FSP concepts in its studies. While part of the power roadmap for NASA, FSP is outside the LunA-10 timeline, as it is currently expected to be fielded on the Moon no earlier than 2040. Additionally, FSP is inherently a point solution, confined to one location on the Moon; it will therefore pair best with a similarly static customer, such as a habitat hosting astronauts or a large-scale mining factory, that can be connected by wired power. There are also significant regulatory hurdles to nuclear power that make easy commercial access challenging. The concepts explored within this chapter are better suited to scaling through the Foundational Age of the lunar economy; the age and time-dependent development aspects are discussed further in chapter 14 of this *Field Guide*.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Storm, Lapin, Kennedy, Whitener, Mack, and Petrillo are from Fibertek Inc.
2. Authors Turse and Saldana are from Redwire Space Solutions.
3. Authors Riley and Gorman are from Radar Applications Incorporated.
4. CACI.
5. Axta Space Corporation.
6. Authors Miga and Re are from Advanced Space.
7. Authors Hopkins, Smugeresky, and Lim are from Blue Origin.
8. Authors Nugent and Marshall are from PowerLight Technologies.
9. Authors Fortuin, Van Ness, Sanigepalli, Margulieux, Naclerio, Burrell, Bergman, Zacny, Klein, Clay, Begland, Hubbard, and Glazer are from Honeybee Robotics.
10. Defense Advanced Research Projects Agency (DARPA).
11. Jaffe, *Power Beaming*.
12. Lubin, "Moonbeam Lunar Beamed Power."
13. Storm and Hovis, "Space Lidar Technologies"; Kearns, "NASA Funds Laser Communications Tech"; NASA, "Lunar Lidar Technology" for Artemis Human Habitation"; and Storm and Mathason, "Small Satellite Optical Communications."
14. Regulated power: Final electrical power available to a user.
15. Shinora's equations are used since wireless power transmission is a near-field effect. For a far-field effect (where one can assume a plane wave at far field), the Friis transmission equation would be more appropriate.
16. Thomas et al., "Modular AC to DC Interface Converter."
17. Barchowsky et al., "A High Voltage Tethered Power System for Planetary Surface Applications."

5

Lunar Mining

Edited by Michael Nayak

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5.1 Introduction and Framing

During the California Gold Rush, Levi Strauss and Jacob Davis sold shovels and wheelbarrows before inventing the riveted-pocket work pants known as jeans. The Gold Rush's first millionaire, Samuel Brennan, made his fortune monetizing services for gold miners, such as picks, shovels, and pans. There is a historical model behind providing services to mining operations that are monetizable and ultimately become profitable.

Let us begin with a discussion about the "anchor tenant" for the lunar economy.

Power (chapter 4), communications/navigation/timing (chapter 7), robotics (chapter 8), construction (chapter 9), and mobility/logistics (chapter 12) are examples of commercial services that may be monetizable and have infrastructure value, but a question then arises: *services to support what?* The utility case at the center of the economy is the *anchor tenant*, around which all other services are based. For the Gold Rush, the anchor tenant was gold, and the service that made the first millionaires was equipment. Law enforcement, transportation, and mobility (transcontinental rail) quickly followed.

What is the anchor tenant for the Moon?

Today, it is in situ resource utilization (ISRU). Unlocking a sustainable human presence on the Moon depends on the ability to use local resources. Resources abundant on the Moon include solar power potential, oxygen, and a variety of useful metals. A complete ISRU-based lunar economy will need to develop industries that can utilize all available resources.

Today, the clear forerunner for specific resources worthy of mining is oxygen for in situ propellant (liquid oxygen) creation. Much of this chapter will focus on ISRU oxygen, extracted from lunar regolith. There are, however, other possible *future* anchor tenants. As of the writing of this book, we have next to no knowledge about the subsurface composition of the Moon. Before gold was found in California, wealth was created in the West from the fur trade. In fact, some of the early infrastructure that benefited the Gold Rush was built for the fur trade. It is possible that oxygen and water are merely today's lunar fur industry—a starting point from which a future "gold nugget" may be found, lying beneath the surface of the Moon. Lunar services such as communications, power, and mobility will then serve that new anchor tenant in much the same way, *as long as each service is rapidly scalable*.

This chapter will focus on two methods being actively developed for commercial ISRU focused on oxygen or energy from oxygen products: molten regolith electrolysis (MRE) and carbothermal reduction. Two conceptual designs for minimum viable experiment systems will be outlined, together with their scaling to large-scale production on the Moon. Challenges with scaling, dust, thermal, and 1/6-g lunar gravity will also be discussed.

5.2 Introduction to Oxygen Extraction

Lunar oxygen, comprising over 40 percent of the lunar regolith, is often trumpeted as the key to the development of transportation (propellant), to life support for the lunar economy, and to power future exploration of the solar system.[5] The most common form of spacecraft propulsion is chemical propulsion, requiring fuel and an oxidizer. The oxidizer is usually liquid oxygen (LOX).

LOX can constitute up to 70 percent of a rocket's overall propellant weight, thereby greatly affecting the launch cost. There are mature terrestrial industries for the manufacturing of LOX and propellant, but the current cost of launch is prohibitive, and vehicle wear and tear to escape the Earth's gravity is high. Development of oxygen production facilities on the Moon, with its much lower escape velocity, is a desirable goal for the manufacturing, stockpiling, and provisioning of LOX off-planet.[6] A near-term user has been identified: SpaceX's Super Heavy first stage booster for Starship will be the largest known user of LOX, calculated at 2,650 tons of LOX per vehicle. The Starship spacecraft itself has a propellant capacity estimated at 936 tons of LOX.[7]

The successful implementation of lunar oxygen production could reduce dependence on costly and logistically complex resupply missions from Earth, enable the establishment of fuel depots and fueling stations to drive down the costs of interplanetary missions, and ultimately make the solar system more accessible.

5.2.1 Solid Oxide Electrolysis Cell and Molten Regolith Electrolysis

This section presents an investigation conducted under LunA-10 into the MRE process, designed to extract high-purity oxygen from lunar regolith. It will address unique challenges presented by the lunar environment, including pervasive lunar dust, dynamics of molten regolith flow under reduced gravity, and the need to balance system performance with long-term survivability. As with lunar power, commercial lunar mining must be pursued with a scalable strategy. Economic considerations play a crucial role in commercial lunar oxygen production. This section will also briefly explore evolving pricing dynamics anticipated in the maturing lunar market and identify key external cost drivers.

Solid oxide electrolysis cell (SOEC) has been successfully implemented on Earth for the extraction of metals or alloys from their oxides. SOEC can fabricate a broad spectrum of metals and intermetallic compounds, such as tantalum, titanium, magnesium, and aluminum.[8] This foundational technology can be modified to extract oxygen from lunar regolith as part of MRE.

The core components of the electrolytic cell encompass an anode assembly, a cathode assembly, and an intervening membrane. An electric current is passed through the molten regolith mixture, causing oxygen ions (O^{2-}) to migrate through the solid oxide membrane toward the anode and be released as oxygen gas (O_2):

$$2O^{2-} \rightarrow O_2\ (\text{gas}) + 4e^-\ (\text{at anode})$$

The remaining metal cations (e.g., Fex^+, Six^+) in the melt are reduced at the cathode, forming the desired metals. Both anode and cathode assemblies are characterized by a catalyst layer deposited on a current collector; yttria-stabilized zirconia is the preferred membrane material for the SOEC.[9] It exhibits high oxygen ionic conductivity and selective conduction of oxygen ions. A tubular design approach allows a split in the medium; oxygen production occurs on the anode side with the zone where the corrosive melting regolith is present, which prevents anode corrosion. The tubular cell design is at Technology Readiness Level 3 and is a pivotal piece of the SOEC scaling strategy, as it demonstrates the efficacy of the isolation zone where oxygen is generated, segregated from the harsh and corrosive environment of the lunar regolith.

The regolith feedstock significantly impacts the MRE process. While bulk oxygen content is relatively similar across the Moon,[10] there are key compositional property differences between regolith at lunar poles and at the equator. Polar regions experience periods of permanent shadow, allowing for cold trapping of volatile elements like hydrogen, water ice, and other compounds. These volatiles are scarce or absent in equatorial regolith. These volatiles might introduce additional complexities during MRE processing; for example, this may require pre-sintered regolith or the need to allow venting.

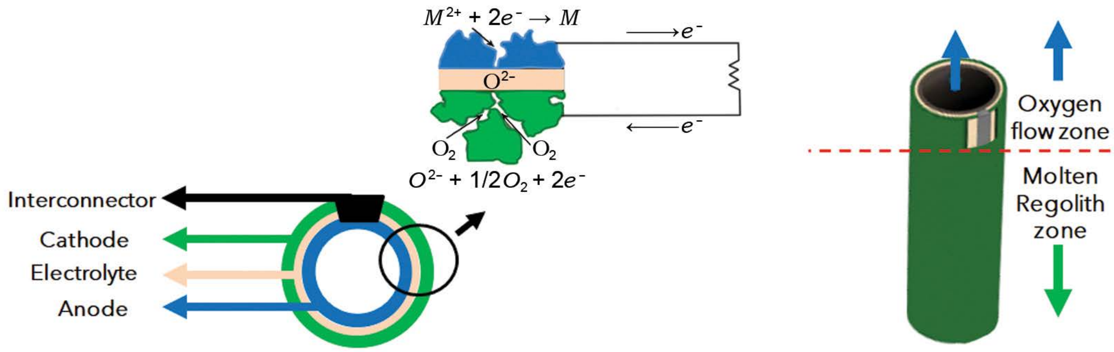

Figure 5.1. (Left) Cross section of a tubular cell. (Right) Top up view of tubular cell. [Credit: Helios Project Ltd.]

More practically, the high viscosity of molten regolith, particularly in the presence of partially molten oxides, can hinder its flow within the MRE reactor. This can lead to an uneven distribution of feedstock material and affect oxygen production efficiency. Denser components within the regolith melt, such as metallic oxides, might settle at the bottom of the reactor. Therefore, MRE requires optimized heating strategies to maintain low viscosity for effective flow and circulation patterns to counteract settling and promote uniformity. The abundance of target oxides like ferrites and silicates and the presence of impurities can influence the electrolysis reactions and might require adjustments in operating temperature and reactor pressure. Beneficiation of the regolith feedstock, or pre-processing the regolith to enrich specific minerals, may be necessary to optimize the process.[11]

The presence of iron oxides, silicon oxides, and alkali oxides can affect the efficiency of the MRE process in several ways.

- Electrical conductivity. Iron oxides enhance electrical conductivity of the molten regolith, potentially improving efficiency.
- Slag formation. Silicon oxides can react with other components in the MRE system to form a slag layer that can impede oxygen bubble formation and reduce efficiency.
- Electrolyte degradation. Alkali oxides can react with the electrolyte material, leading to its degradation and reduced effectiveness over time.

Transferring and managing large volumes of gas can be cumbersome in a lunar environment with limited pressurization capabilities. Liquid oxygen is denser than oxygen gas, requiring less storage volume and cryogenic temperatures (77 K) or pressurization to remain in liquid form. Maintaining these cryogenic temperatures presents a significant engineering challenge in the harsh lunar environment, necessitating complex and energy-intensive storage and transportation systems.

MRE also generates a valuable byproduct: heated deoxygenated regolith (DOR). After electrolysis, which separates oxygen from metal oxides in the regolith feedstock, the remaining material is primarily composed of elemental metals. This byproduct exits the MRE process at high temperatures. The mechanical properties of this silicate-rich, bulk, glassy regolith make it a promising candidate for construction of lunar habitats, landing pads, and other structures.[12] Due to the reduction of ferrites as the electrolysis progresses, DOR is expected to have a higher melting point of about 600°C. This energy gap makes it difficult to be reheated later but makes it suitable for use in lunar environments that suffer from significant thermal fluctuations.

New insight from LunA-10: While heated, DOR is a viable commercial product for resale in a lunar economy to a secondary user such as a metal recycling foundry (see chapter 6).

The presence of both metallic and residual oxide components in the DOR creates a *cermet* (ceramic-metal compound), which exhibits the strength and heat resistance associated with ceramics and the potential for electrical conductivity or ductility found in certain metals.[13] These properties are beneficial for manufacturing tools and equipment for lunar construction or resource processing.[14] However, the microstructure of the DOR material will influence the distribution of metallic and oxide phases and its overall properties; further characterization using in situ testing is needed.

5.2.2 Conceptual Design of a Minimum Viable Experiment (MVE) System

This section discusses progression from an MVE demonstrator to maximum performance units (MPU), with the goal of ultimately establishing a large-scale oxygen production plant (OPP). A commercial design from Helios Project Ltd. is used to illustrate this scaling.

The MVE uses a hopper design to feed regolith into the bottom of the reactor chamber. This forces molten regolith to travel upward through the reactor for processing. A heated jacket around the inlet path ensures consistent regolith flow, further controlled by a weight sensor and a flow restriction mechanism. Heating rods within the reactor provide additional thermal energy to liquefy the regolith. These rods work alongside specialized process rods (housing the SOEC cell assembly) that extract oxygen from the molten material.

As the regolith flows upward through the reactor, its contact surface area with the electrodes progressively increases, maximizing oxygen extraction. The extracted oxygen rises to a collection chamber at the top of the reactor before transferring to an intermediate storage tank (fig. 5.2). Next the processed regolith—now DOR—exits the reactor chamber through holes at the top. It then flows down to a dedicated DOR collection chamber equipped with control elements to measure flow for added process control. From this chamber, DOR can be carefully discharged to a collection chamber or directly delivered to a partnering service provider who might utilize the hot DOR as a resource (see section 6.4.1 for more details).

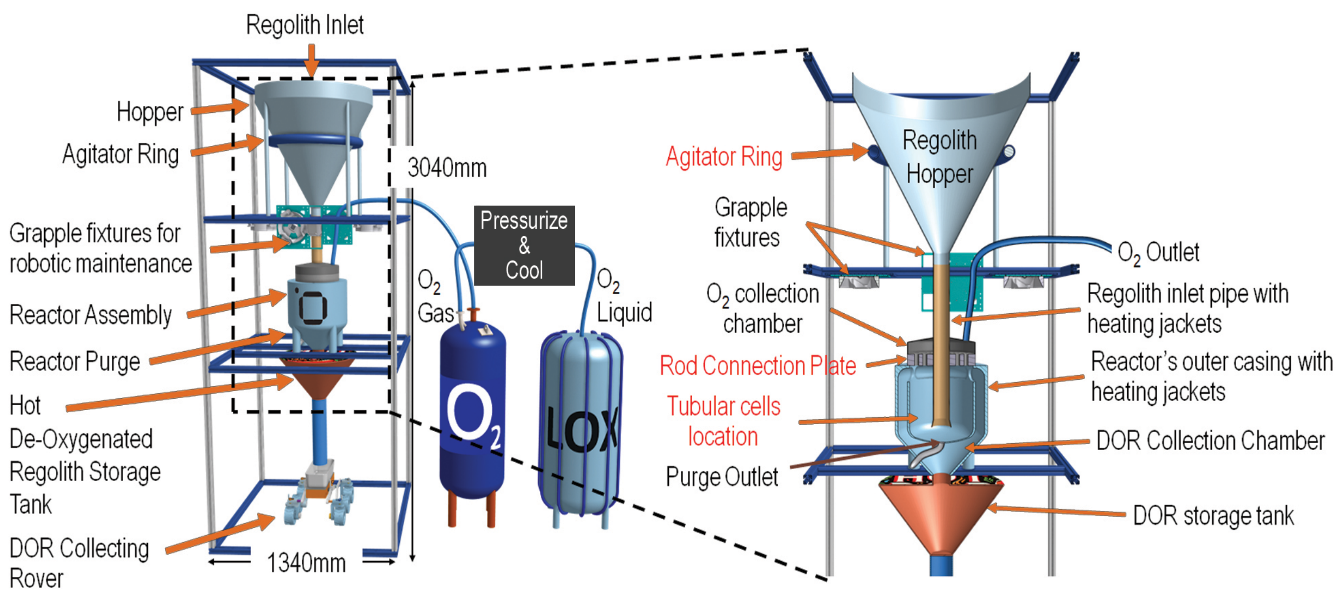

Figure 5.2. (Left) MVE System concept for lunar oxygen. (Right) MVE reactor cross section. [Credit: Helios Project Ltd.]

The MVE unit's power consumption can be broken down into three main categories:

- Heating. Most of the power (17 kW) will be used for heating and to maintain the regolith in a molten state.
- Electrochemical oxygen extraction. The extraction process will require a steady supply of 3 kW at 100 percent duty cycle.
- Night survival. To survive the lunar night without continuing mining operations, the system will require minimal power (10 W) to maintain operational temperatures and critical functions.

The MVE unit targets the production of 250 kg of high-purity oxygen (zero-grade O2) per month, from a regolith input of 1,250 kg. The system design will incorporate all essential subsystems for oxygen production, including regolith handling, processing, oxygen extraction, and mechanisms for oxygen and DOR storage.

As part of LunA-10, Helios Project Ltd. developed a strategy for scaling up the MVE system, culminating in a robust oxygen production plant (OPP). The target customer would be SpaceX's Starship and refueling its LOX tanks; SpaceX was also a part of the LunA-10 consortium.

The MVE scales to a maximum performance unit, the largest MVE system possible to maintain regolith mass transfer and oxygen production efficiency. The MPU can generate significantly higher oxygen production capacity of 5,000 kg per month (twenty times greater than MVE). This will require a proportionally larger regolith input of 25,000 kg per month. This is a significant input to an immobile plant; chapter 8 discusses Robotics as a Service (RaaS) that could be purchased to continuously supply this monthly regolith mass from nearby regions.

A large-scale oxygen production plant is housed in a 20-foot shipping container, which can be loaded into a single Starship. The OPP consists of an array of MPUs operating in unison. Every three MPUs will be fed from the same hopper. All MPU oxygen outlets will be bridged to an oxygen gas tank. The OPP aims to achieve an oxygen production capacity of 200 metric tons per month. To sustain this production level, the OPP will need substantial regolith: 1,000 metric tons per month.

Analysis showed the importance of collaboration for large-scale lunar oxygen production. This was directly in line with the goals of the LunA-10 program.[15] Some areas of collaboration are:

- Transportation: deployment to the lunar location and unloading;
- Regolith handling: robotically enabled lunar regolith excavation, transportation, and delivery to the OPP;
- Electrical power: reliable power supply to meet the significant energy demands of the oxygen production process. An OPP-scale unit would be a primary user of MWh-level wired or wireless power (chapter 4); and
- Communication infrastructure: for real-time monitoring and production control.

5.2.3 Regolith Flow Dynamics and Lunar Gravity Challenges

The dynamics of the molten regolith flow in lunar gravity raise several challenges crucial for optimizing reactor design and performance:

- Reduced buoyancy-driven convection. Convection currents in a molten material arise due to buoyancy forces. These forces cause warmer, less dense material to rise, while cooler, denser material sinks. Under lunar gravity, the buoyancy-driven convection will be weaker, potentially leading to stagnant zones within the melt and hindering mass transport of oxygen ions.
- Reduced settling velocity. Denser components, such as metallic oxides, tend to settle at the bottom of the melt due to gravity. The weaker lunar gravity will result in a slower settling velocity compared to Earth. This can still lead to uneven distribution of feedstock material within the reactor over time, potentially affecting production efficiency.
- Maintaining a stable melt flow. Weaker gravity makes it more difficult to maintain a stable molten regolith flow through the reactor. Surface tension effects might become more dominant, leading to pooling of the melt around the electrodes and exposing other areas to cooling and solidification.

Several approaches were investigated to ensure optimal MRE reactor performance:

- Reactor geometry optimization. Encouraging circulation patterns within the melt through careful geometric design can counteract the reduced buoyancy-driven convection. Computational fluid dynamics (CFD) simulations were used to optimize the reactor chamber geometry for lunar gravity, including the shape and size of the melt chamber and the positioning of electrodes. Developing and validating computational models that accurately predict regolith flow dynamics under lunar gravity conditions will be an essential MVE objective.

- Electrode design and positioning. The design and positioning of the electrodes can influence regolith flow patterns in the vicinity of the reaction zone. Tilting the electrodes, or incorporating other features, to promote upward flow near the electrodes can help maintain a stable molten regolith interface and enhance mass transfer rates. Ensuring a steady flow of the melt past the electrodes promotes uniform feedstock consumption and extends electrode lifespan. Optimized flow patterns facilitate heat transfer within the melt, minimizing solidified regions and ensuring uniform operating temperatures throughout the molten regolith. Smooth flow of the melt past the electrodes is crucial for maximizing mass transfer of oxygen ions and optimizing electrical conductivity.
- Thermal management. Maintaining a uniform temperature distribution within the molten regolith prevents solidification of the material. Regolith flow patterns should facilitate heat transfer from external heating elements throughout the melting, such as additional heating rods inside the MRE reactor.

5.2.4 Commercialization of Lunar Liquid Oxygen

A material hurdle to creating a sustainable lunar economy is *new value creation*, not simply the transference of value within a closed loop. To achieve a sustainable presence on the lunar surface, lunar activities and business opportunities must generate a profit and a return on investment. An initial exploration of oxygen and LOX profitability—by understanding pricing dynamics over time and cost drivers—was conducted as part of LunA-10.

Pricing for lunar oxygen is anticipated to progress through at least three key phases, with pricing trending downward before reaching a plateau, as supply and demand evolve.

Phase 1: Beginning. MVE demonstration. There will be minimal customers (one or two) and minimal lunar suppliers (one or two). Willingness to pay for any resource on the Moon must consider the alternative of paying to bring the resource from Earth; this is the primary source of competition in this phase. Transportation cost from Earth to the lunar surface is estimated at \$1.0–1.2 million/kg.[16] Oxygen production is contracted at least one year in advance.

Phase 2: Growing. MPU establishment, building on lessons from MVE demonstration. Output volume increases. There will be growth in capacity both from the initial supplier and the entry of new producers. The number of customers will also increase, heralding the beginnings of competition for lunar oxygen. As scale efficiencies are realized, prices begin to fall relative to the cost to bring this resource from Earth. Oxygen production is still purchased in advance (locking a customer to a specific producer for each contract) but with lead times under one year.

Phase 3: Expanding. Rapidly expanding capacity through multiple distribution networks operated by multiple lunar oxygen suppliers. Suppliers will compete for multiple customers' business, with lunar oxygen becoming its own market. There will be enough activity to achieve market-based pricing that moves with supply/demand changes. Prices for transportation from Earth and production of lunar oxygen stabilize. Lead times and pricing vary, but for factors other than simple production capacity (e.g., distance to a fueling station, number of nearby fueling stations, long-term business relationships). For example, a 2,000-ton order to be delivered at a remote location serviced by a single producer for a new customer will likely cost more per ton than a 15-ton purchase at an industrial hub with competition from multiple producers for a repeat customer. There is enough production and sales activity for investors to apply commodities trading principles akin to those on Earth. This could have a smoothing effect on prices or drive speculative behavior. Section 17.5 of this *Field Guide* discusses a lunar commodities exchange in greater detail.

5.3 Extracting Oxygen and Energy

Long-term lunar infrastructure requires heat source(s) to survive the extreme cold during lunar night. Centralized energy storage to provide a heat source and electricity during the lunar night can enable simplified design for all hardware on the lunar surface. This section explores an alternate concept for mining oxygen, namely carbothermal oxygen production from lunar regolith, conjoined with the commercial capability for electrical energy storage.

The hardware required for carbothermal oxygen production and electrical energy storage can convert methane, hydrogen, oxygen, carbon monoxide, and water into one another as long as mass balances are maintained. This chemical conversion can help balance supply and demand in the lunar economy. This section will use the Lunar Oxygen Production and Energy Storage (LOPES) node from Sierra Space as a representative example to illustrate this ecosystem.

The initial reactors must effectively demonstrate the technologies required for large-scale operation to show a viable path to mass production. The lunar environment provides unique challenges for automated systems. Tolerance to the reduced gravity conditions, lunar dust, thermal environment, and maintenance procedures must be designed into systems prior to launch. This section will discuss these challenges and commercial opportunities. Regolith, propellent ullage, daytime electricity, and communication services will be purchased from external vendors while oxygen, water, DOR slag, and nighttime electricity are sold to consumers.

5.3.1 Connecting Oxygen Production to the Lunar Ecosystem

In addition to the previously discussed benefits to reducing launch mass with LOX, indigenously produced oxygen has synergistic overlap with fuel cell–based electrical energy storage for lunar night survival. An initial discussion of fuel cells is provided in section 4.4.

Surface temperatures during lunar night reach 41 K, which causes thermal stresses in electronics and mechanical systems. As energy storage capacity grows, lunar night operations become possible and scalable. Recycling high-value materials will minimize total system launch mass by helping to close the lunar economy consumable loop. Combining indigenously produced oxygen with recycled material adds architectural flexibility that further reduces overall launch mass.

A key concept from LunA-10 is waste from one asset may be useful in a transformed state to another asset and thereby monetizable. Examples of chemical recycling include combining hydrogen or methane propellent with oxygen to make water, instead of venting them. This water could be sold as is or split back into hydrogen and oxygen for a fuel cell–based rover. These can later be returned in the form of water. This system could offload an Environmental Control and Life Support Systems (ECLSS) CO2 removal system or break down CO2 refrigerants while capturing the oxygen and carbon. Due to the lack of carbon on the Moon, the excess carbon from methane or carbon dioxide can be useful for ISRU-based steel manufacturing (explored further in chapter 6).

The LOPES Node is an architecture (fig. 5.3) that integrates carbothermal reduction of lunar regolith, water electrolysis, methanation (Sabatier), and fuel cells into a single system. These technologies create a highly synergistic integrated architecture.

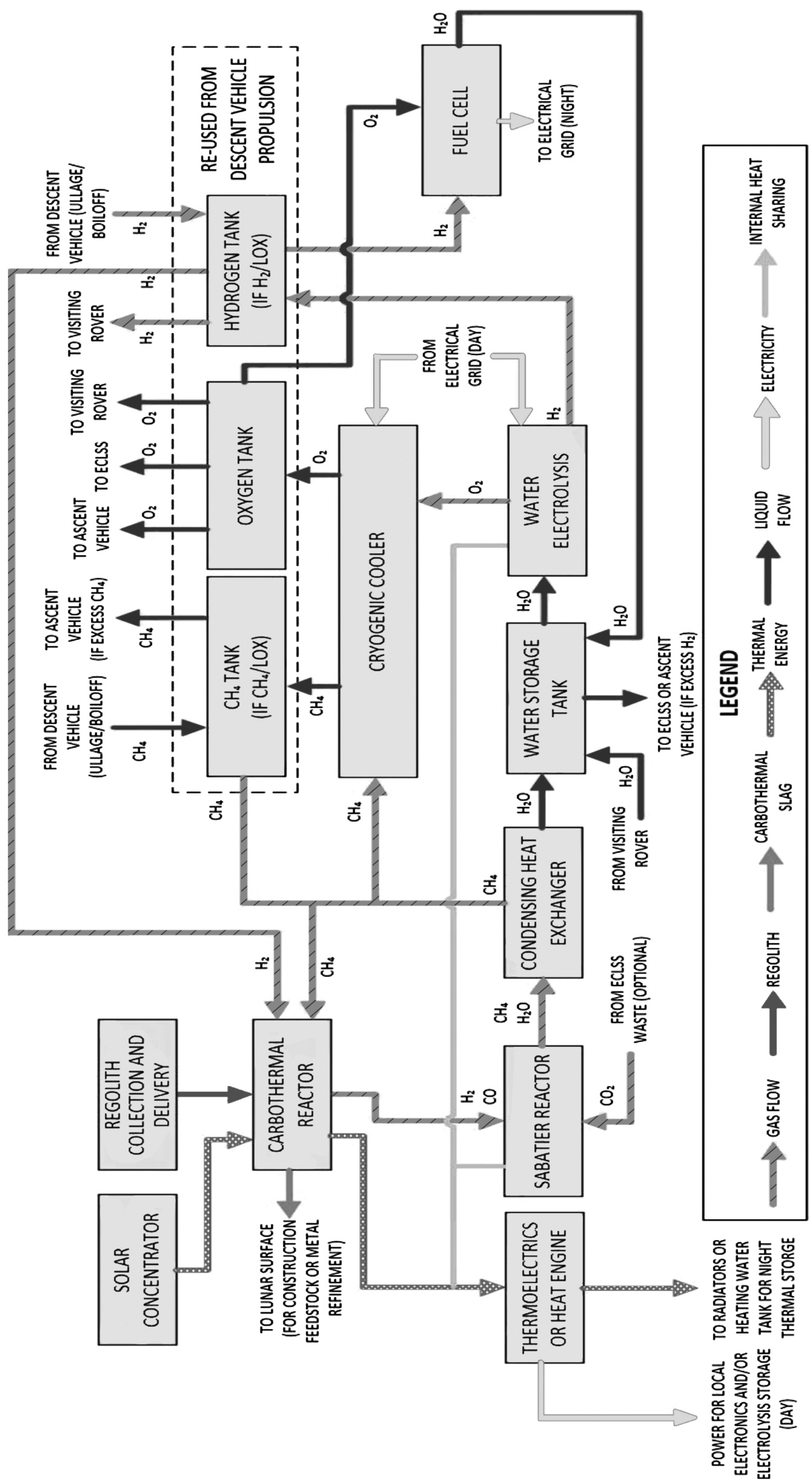

Figure 5.3. Lunar Oxygen Production and Energy Storage Node System Architecture. [Credit: Sierra Space]

5.3.2 Introduction: Oxygen Extraction, Energy Storage, and Recycling

For *oxygen extraction* by carbothermal reduction, lunar regolith is heated in the presence of a carbon source (for example, methane). Methane pyrolyzes on the molten surface of the regolith, depositing the carbon. The carbon then diffuses into the molten material and reduces metallic oxides within the lunar regolith to create carbon monoxide. Methane pyrolysis and carbothermal reduction are conducted as one step inside the carbothermal reactor:

$$xCH_4(g) + MO_x(l) \rightarrow xCO(g) + 2xH_2 + M(l)$$

Excess hydrogen from the pyrolysis and carbon monoxide are swept into a downstream methanation reactor. The methanation catalyst enables conversion of the carbon monoxide and hydrogen into methane and water. Newly formed methane is recycled back into the carbothermal reactor to be reused, while a condensing heat exchanger removes the water from the process stream.

$$3xH_2(g) + xCO(g) \rightarrow xCH_4(g) + xH_2O(g)$$

The water is electrolyzed, and the oxygen is stored, while the hydrogen is recycled back into the methanation reactor. The methanation reactor combines carbon monoxide with hydrogen to produce water and methane. Next, water is split using electrolysis:

$$xH_2O(l) \rightarrow xH_2(g) + 0.5xO_2(g)$$

Combining the above steps, the net chemical reaction becomes:

$$MO_x(l) \rightarrow M(l) + 0.5xO_2$$

This creates a closed process architecture where the extraction is primarily driven by heat, not electrical energy. Excess hydrogen released from the methane pyrolysis and electrolysis is recombined with the carbon from the carbon monoxide carrier. The only inputs are lunar regolith (metallic oxides) and energy, and the only output is oxygen and slag (deoxygenated metallics). This eliminates consumables transported from Earth.

Energy storage. Temperatures as low as 94 K (equator) and 41 K in the polar regions cause large thermal stresses in mechanical systems and are too cold for most conventional electronics.[17] Due to the relatively long lunar night on most of the lunar surface, large quantities of electrical energy storage are required at unfavorable temperatures.

When paired with ISRU-based oxygen, a fuel cell is ideally suited to produce electrical energy for lunar night energy storage. Using oxygen extracted from lunar regolith to store electrical energy provides nearly 90 percent of the chemical mass required for energy storage when using a fuel cell. Empty propellent tanks on descent vehicles could provide volume for oxygen and hydrogen storage. The carbothermal oxygen production process already uses water electrolysis units to re-split the fuel cell–generated water during lunar day.

A key insight from LunA-10 is: For chemical recycling, the integration of fuel cell–based energy storage with lunar oxygen creates a unique capability to recycle chemicals present within the anticipated lunar architecture. Recycling the propellent ullage from lunar vehicles (methane, hydrogen, and oxygen), excess ECLSS waste (fecal matter, CO2, plant matter), or other sources (CO2 refrigerants) enables use of material that would otherwise be wasted.

As an example of the importance of recycling, a single SpaceX Starship landing is expected to vent roughly 10 tons of methane propellent ullage to the lunar atmosphere. When combined with ISRU-based oxygen, the hydrogen contained in this methane could create 22,500 liters of water. Similarly, water has life support uses, can be used as cold gas propellent, and, when paired with electrolysis, becomes a non-cryogenic means of oxygen and hydrogen storage. Carbon is desirable on the lunar surface to produce steel. Lunar regolith contains roughly 5 percent to 20 percent iron oxide.[18] Iron is the easiest metallic oxide to reduce within the lunar regolith. Limited lunar carbon sources exist to further process this iron into steel, except for methane ullage as a source of carbon.

5.3.3 Notional System Design and Concept of Operations

Using the methods described above, LOPES aims to provide liquid oxygen, nighttime electrical energy, and chemical conversion services to consumers. This process has five main subassemblies for operation: the carbothermal reactor, the methanation reactor, water electrolysis, chemical storage, and a fuel cell.

Carbothermal reactor. Regolith is mined with a rover and lifted to the top of the reactor by robotic arms or vibratory inclines. The regolith enters an unpressurized hopper, is metered using a dosing valve, and is then deposited into the reactor through a pair of pressure sealing valves. Two pressure sealing valves acting as an airlock are required to bring the material into the pressure volume without venting the reactor volume. Regolith is transported to the reaction site, where it is heated with concentrated light. Once the reaction cools, a rake picks up the slag and deposits it onto the lunar surface through a second pair of pressure sealing valves. The rover then removes the slag. Chapter 8 discusses Robotics as a Service and integration with lunar ISRU activities such as those discussed in this chapter. Chapter 12 discusses how rail surface preparation activities can be synergistic with the need for ISRU plants to ingest regolith regularly.

The reactants must reach 1625°C for the carbothermal reaction, although higher temperatures are more favorable. High-temperature lunar regolith is extremely corrosive and will corrode the container walls.[19] Therefore, the carbothermal reduction step uses a direct energy approach, where concentrated light is applied directly to the surface of the lunar regolith. This eliminates direct contact between the molten material and support structure.

Incoming concentrated light is simply stopped to halt the reaction. The slag is then allowed to cool and solidify. This makes starting and stopping the reactor straightforward for lunar night or maintenance activities. This approach is enabled by the extremely low thermal diffusivity of bulk lunar regolith.[20]

Practically, when melting lunar regolith, the molten material has a much higher thermal diffusivity due to the increased conductivity, which then increases size while limiting the thermal gradient through the unmelted material. An experiment conducted by Sierra Space used the direct heating approach on GreenSpar 250 simulant, which showed a thermal wave diffusion depth, to the melting point of the material, of only 2.2 cm deep into the regolith despite 900 W applied over twenty minutes.

The methane atmosphere directly above the reaction site must be carefully controlled. Too little methane will starve the reaction from carbon, hurting performance. Too much methane will deposit carbon onto the surface of the reaction site faster than it can diffuse into the volume of the molten material. This creates a carbon film over the surface of the reaction site, shutting down the reaction. However, if carbon demand exists (for example, biomining, discussed in chapter 20), this could be exploited to purposely separate the carbon from the methane.

Methanation reactor. The methanation reaction is exothermic. The reactor is heated to initialize the reaction but then must be cooled to prevent methane from pyrolyzing inside the reactor, coking the catalyst.

Sabatier reactors have been used on the International Space Station (ISS) for ECLSS CO2 removal systems and are at a Technology Readiness Level of 9 (the most mature).[21] The ISS Sabatier (methanation) reactor reacts CO2 with hydrogen to make methane and water. This reaction is broken down into two steps. The first is the reverse water gas shift reaction that makes carbon monoxide and water:

$$CO_2(g) + H_2(g) \rightarrow CO(g) + H_2O(g)$$

Next, the carbon monoxide is further reacted with hydrogen to make water and methane:

$$CO(g) + 3H_2(g) \rightarrow H_2O(g) + CH_4(g)$$

The carbothermal reduction of lunar regolith produces CO and therefore relies on the methanation step. This simplifies the system as a single step methanation reaction is required. However, if markets for CO2 chemical conversion exist, implementing the reverse water gas shift in addition to the methanation reaction step is straightforward.

Water electrolysis. The carbothermal and methanation processes produce water as the oxygen carrier. While water is a valuable resource for certain aspects of the lunar economy, producing pure oxygen requires one final step: electrolysis.

Electrolysis is energy intensive. On Earth, commercial electrolyzers need 5 to 7 kWh to separate 1 kg of water. In a lunar setting, 4.4 kWh is required to separate 1 kg of water, assuming no efficiency losses. A reversible solid oxide cell (rSOC) that performs both electrolysis and fuel cell operations can consolidate mass.

A solid oxide electrolysis cell (SOEC) needs both thermal and electrical power to function and has an operational temperature of 600–800°C. The thermal energy can be provided using the waste heat from the carbothermal reactor.

Liquification and chemical storage. The oxygen created from electrolysis is formed as a hot gas and must be cooled into liquid oxygen for long-term storage and rocketry uses. Long-term storage must maintain a cryogenic temperature below the boiling point of oxygen. Cold temperatures also increase the density, reducing tank size and mass slightly.

Estimating the energy required to cool oxygen into LOX is broken into three steps: energy to cool oxygen to the boiling point, energy for phase change, and energy to cool to the holding temperature. Creating five metric tons of oxygen per year was used as the initial plant scale. Using the lumped mass approximation for the MVP plant, thermodynamic values, and commercial-off-the-shelf efficiencies for spaceflight rated cryocoolers, the energy values are shown in table 5.1.[22]

Table 5.1. Cryocooler latent and sensible energy usage for an MVP-sized plant

Temperature Range (K)	*Cooling Power (W)*	*Electrical Power (W)*
423 to 90.2	163	1483
90.2	114	1305
90.2 to 80	9.2	123

Roughly 45 percent of the electrical power is needed for the phase change from gas to liquid. This energy requirement cannot be reduced. However, the initial cooling energy can be reduced by precooling the oxygen directly with radiators or regenerative heat exchangers.

Fuel cell. To reduce system mass and complexity, the fuel cell in the LOPES Node is the same unit as the electrolyzer, but it is run in reverse. This is known as a reversible solid oxide cell which has three key benefits: reduced payload mass, increased resistance to chemical poisoning, and reduced system complexity. Reusing an electrolyzer array as the fuel cell immediately saves ~15 kg of cell stack mass. Solid oxide cells are also able to use fuels other than hydrogen, including methane, CO, and other hydrocarbons.

The electricity from the fuel cell is intended as a product for external customers during lunar night. Because the infrastructure of manipulating the hydrogen and oxygen is present, this method is more mass efficient than conventional batteries. Fuel cells also have greater specific energy than lithium-ion batteries, reducing mass. Section 4.4 discusses fuel cells from a power perspective.

5.3.4 Lunar Environmental Challenges: Gravity

Environmental concerns must be considered when designing lunar hardware. For example, low lunar gravity impacts two-phase flow regimes and material-handling operations. Lunar dust can damage moving mechanisms and foul radiators and solar panels. Low thermal diffusivity of the lunar regolith, coupled with solar flux, causes significant heating of the surface during the day. Nonuniform incident light angles between the south pole and equatorial regions cause daytime regolith temperatures to differ between locations. At night, temperatures plummet below 50 K.

Gravity. Gravity feed simplifies solid material handling operations within the carbothermal reactor. Gravity feeds solid material out of a hopper and through a dosing valve to separate the slag from unprocessed insulating regolith. Vibration is used to facilitate material flow of the regolith hoppers. Tuning of this vibration under lunar gravity conditions will be required.

After carbothermal processing, rake tines scoop the solidified slag out of the insulating regolith (fig. 5.4, left). Gaps in the tines allow the insulating regolith to filter back down into the reactor. The reduced gravity conditions may affect tine spacing and the speed at which the rake operates to avoid throwing material. The specific geometries used for carbothermal processing will require in situ testing in lunar gravity. Additionally, the carbothermal reaction occurs at a highly complex three-phase site where insulating regolith is melting, methane is pyrolyzing, carbon is diffusing into the liquid regolith, and gaseous carbon monoxide is being released. Carbon monoxide bubbles out of the material due to buoyancy effects and is swept into downstream processes. This has not been tested under lunar gravity conditions. Unfortunately, to inform the reaction site behavior, the timescales required are longer than the limited lunar gravity available using suborbital parabolic flights.

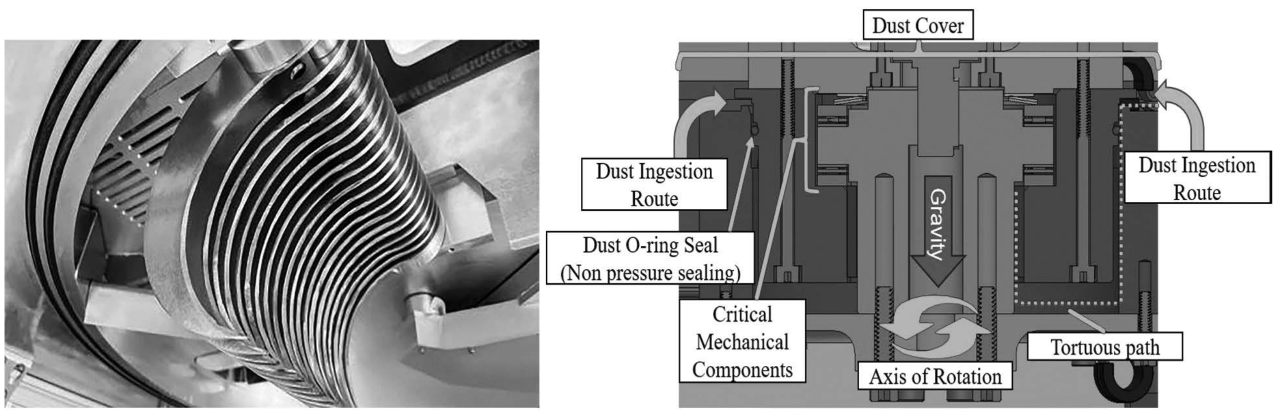

Figure 5.4. (Left) Rake design to separate the slag from the unprocessed regolith. (Right) Rotating joint within a prototype carbothermal reactor that uses a labyrinth pathway to protect against dust. [Credit: Sierra Space]

Because the carbon monoxide formation occurs within the volume of the molten material, bubbles are not required to separate from a surface. This reduces surface tension effects that could prevent carbon monoxide from releasing. Surface tension effects are a documented problem with MRE, where the gaseous oxygen can have trouble separating from the anode in lunar gravity.[23] The effectiveness of LOPES subassemblies in lunar gravity are summarized in table 5.2; these are generalizable to most ISRU applications.

Table 5.2. Effectiveness of subassemblies under lunar gravity

Subassembly	*1/6th G Impact*	*Justification*
Solar concentrator	↑	Less structure is required in lunar gravity for unfolding mechanisms
Regolith collection (Rover)	↓	Reduced gravity lowers friction between rovers and the regolith, this limits reaction forces that can be used for digging operations
Regolith delivery	↑	Reduced gravity allows smaller robotic manipulators to transfer more regolith because less force is required for lifting operations
Regolith hoppers	→	Minor adjustments to wall angles and vibration levels may be required
Regolith transfer mechanisms	→	Minor adjustments to transfer angles and vibration levels may be required
Carbothermal reduction reaction	↑/↓	The carbothermal reaction site is a complex three-phase system. Material is simultaneously melting, pyrolyzing, reacting, and bubbling out of solution. The effect of gravity on oxygen production rates is currently unknown.

Subassembly	*1/6th G Impact*	*Justification*
Slag removal (rake)	→	The reduced gravity conditions may affect tine spacing and operational speed
Methanation reactor	→	Forced gas flow is not significantly affected by gravity.
Condensing heat exchanger	→	While some flow conditions may need to be modified, lunar gravity is sufficient for two-phase separation.
Water electrolysis	→	Solid oxide water electrolysis is conducted through forced flow in the gas phase. Forced gas flow is not significantly affected by gravity.
Fuel cell	→	Solid oxide water electrolysis is conducted through forced flow in the gas phase. Forced gas flow is not significantly affected by gravity.
Cryogenic refrigeration	→	While some flow conditions may need to be modified, lunar gravity is sufficient for two-phase separation.
Liquid chemical storage	↑	Reduced hydrostatic pressures will likely cause lower stresses on containers.
Gas chemical storage	→	Gas storage is not significantly affected by gravity.

Key

↑ Positive impact, lunar gravity makes this process easier than similar Earth systems

→ Negligible impact, some alterations may be needed to accommodate the process in lunar gravity, but no significant challenges or risks are expected

↓ Negative impact, the process is more difficult in lunar gravity compared to similar Earth systems

5.3.5 Lunar Environmental Challenges: Dust

Bombardments by micrometeorites fracture the lunar material and melt particles together. The melted particles combine to create complex and jagged glassy particles called agglutinates. The lunar regolith is typically 25 percent to 30 percent agglutinates but can be as high as 65 percent.[24] Additionally, most regolith particles range between 4 mm and 2 μm.[25] These do not wear down and remain jagged due to the Moon's lack of atmosphere. The solar terminator also creates an electrostatic force that could levitate dust particles above the surface.[26]

This results in a regolith consisting of very small, sharp, hard, electrically charged, and irregularly shaped particles that can levitate themselves onto hardware over long durations. The reduced gravity and lack of atmosphere promote ballistic trajectories, so uncovered agitation will further coat hardware. Managing the dust is critical to prevent premature wear.

Mechanical systems frequently use a combination of passive design features such as felt seals, redundant elastomer O-rings, energized lip seals, and labyrinths to protect components. Figure 5.4 (right) shows an example of a rotating joint designed for dust tolerance. This joint is covered to protect from dust levitation and from robotic loading of regolith. It has a regolith sealing elastic O-ring and a long tortuous path to make it difficult for dust to make it to the critical mechanical components.

Creating reliable, low-leakage pressure seals in the presence of lunar regolith is challenging. Pressure-sealing valves with hardened materials have held up to mare regolith simulants for limited cycles but failed almost immediately when exposed to highlands regolith simulant. An examination of other terrestrial methods for handling abrasive media did not identify any design that could provide the necessary pressure-sealing capability. This forced Sierra Space to develop a new, novel method for providing a pressure-sealing capability tolerant to the abrasiveness of the regolith simulant materials. This system has been tested using GreenSpar 250 lunar highlands regolith simulant for 10,000 cycles of simulant flow through the valve.[27] This design can be adapted to other pressure-sealing applications, including crew air locks.

5.3.6 Lunar Environmental Challenges: Thermal, Location, and Maintenance

Daytime temperatures at the non-polar regions are over 350 K. This is important to cryogenic storage of liquid oxygen as well as integrated system concerns, such as thermal stress across a part where one side is in daylight and one in shadow.

Regolith has a median depth of 2 m to 4 m in the mare regions and 6 m to 8 m in other regions.[28] Regolith reserves are not anticipated to be a limiting factor for short to moderate term; however, it is estimated that it will take a hole 10.6 m in diameter and 4 m deep to supply a SpaceX Starship for a single return journey to Earth using carbothermal reduction of lunar regolith for oxygen. Creating such cavities and supplying regolith to ISRU reactors from beyond the horizon will be commercial support services of direct use to lunar mining companies.

Maintenance for long-duration lunar operation should be conducted using generalized robotic systems. Design for maintenance will be critical. Replaceable components will likely be initially limited to premanufactured assemblies that can be removed and replaced using “pick-and-place” operations from robotic arms (discussed in chapter 8).

Using generalized robots adds additional operational flexibility to recover from faults. This reduces the number of redundant systems and system mass. For example, generalized robotic systems might be able to remove a rock from a hopper that was missed in sieving operations or clear regolith buildup from long-duration operation. Robotic manipulators will likely require both grapple fixtures on the replacement parts, to allow for accurate positioning, and fixtures built into the external surfaces. Grapple fixtures will allow robotic systems to climb and reach the entire external surface. This is discussed further in chapter 8.

5.3.7 Physics-Based Performance Model to Assess Scalability

As part of the LunA-10 program, Sierra Space created a combined semi-physics-based performance model and economic model of the LOPES Node. The relationships output from the physics-based model are integrated directly into the economic model to estimate system production rates, flows, component masses, and power consumption.

The performance model’s main input is the amount of oxygen generated per year. The two primary sizes of interest are an MVP-sized plant (5 metric tons per year) and a plant to serve a SpaceX Starship vehicle (155 metric tons per year). Additional inputs are the efficiencies of the reaction and subcomponents, duty cycle, recycling throughput, and lunar night power generation. The model generates outputs for throughput rates, mass, and power (thermal and electric) for each subassembly within a plant.

The economic model is scaled based on thermal input power to the reactor (kW), power sold to customers during lunar night (kWe), and the amount of water recycled from fuel cell powered vehicles (kg/year). The thermal input power, carbothermal efficiency of the reactor, and the lunar duty cycle (location dependent) are used to calculate the heat rejection requirements (kW) and the amount of oxygen produced during a time period. The electrical power required to operate the system and the amount of slag produced are estimated based on the oxygen production rate. The economic portion of the model estimates the impact of launch costs and demand on operating costs, profit margin, and return on investment. It is also used to determine the appropriate size for an MVP plant size that could be launched and landed on a single descent vehicle.

Using the amount of power sold to customers during lunar night, the model calculates the required oxygen and hydrogen consumption rates (kg/hr). The water electrolysis unit’s water consumption rate (kg/hr) is calculated by combining the water required to produce oxygen for fuel cell consumption, vehicle consumption, and oxygen produced as an end-product. The energy required to split water (kW-hr/kg) is calculated by dividing the enthalpy of formation of water by the electrical efficiency of the electrolysis unit. This is multiplied with the water consumption to calculate the electrical power (kW) required to operate. The mass of the water electrolysis unit is based on user input of power density (kg/kW).

Assuming all the oxygen created in the water electrolysis unit is liquefied, the thermal power (kW) required to liquefy the oxygen is calculated by multiplying the mass of oxygen produced, the specific heat capacity of liquid oxygen, and the temperature difference between ambient and liquefaction temperature, then dividing by the time required to produce the oxygen. The thermal power required is then divided by the electrical efficiency of the cryocooler (assumed as 5 percent) to give the electrical power (kWe) required to liquefy the produced oxygen during operation. The mass of the cryocooler is calculated by dividing the required thermal power by the estimated energy density of a cryocooler based on existing systems.

Heat rejection requirements for each subsystem are summed to find the total heat rejection requirement for the system. The carbothermal reactor accounts for most of the waste heat generated and is calculated based on the efficiency demonstrated in a lab. The total heat rejection requirement is used to calculate an estimated radiator mass, which is then fed into the launch cost calculation.

The cost of third-party services such as regolith delivery, slag removal, and electrical power are also calculated in the model. Electrical power is based on feedback from other LunA-10 companies or calculated based on the power density, life span, and associated launch costs of solar panels. The mass of the required solar concentrator system is calculated by dividing the electrical power required by the energy density of an existing solar system (kg/kW). The solar concentrator system mass is then multiplied by the launch cost ($USD/kg) and the lifespan to give the cost of electricity ($USD/kW-hr) during a single lunar day.

The cost of regolith delivery and slag removal is based on the time for a robotic rover to deliver the material and the cost per hour of rover time. As part of LunA-10, collaboration with robotics company GITAI led to a method for calculating the rover time required for delivery operations. Per-hour robotics costs used in the model are discussed further in chapter 8.

Beneficiation consists of sifting regolith down to a particle diameter of less than 1 mm. The ratio of the regolith usable after sifting is the beneficiation ratio. Mass of the delivered regolith is dependent on the scoop size (50 kg) and the beneficiation ratio. The mass of usable regolith in a delivery is then used to calculate the cost of regolith delivered per kg. The cost of slag removal is calculated similarly, except that there is no beneficiation ratio for slag. Any slag sold would cover the removal cost of itself, in addition to some nominal value beyond the transportation cost.

Revenue, cost, profit, and return on investment for the ISRU plant are calculated by the model. The costs are divided into operating costs and initial costs. The total initial cost of the ISRU plant is modeled as sum of the total launch cost and the total development cost. The total launch cost is the total system mass multiplied by the launch cost per kg. The development cost is a user estimated input based on similar projects in recent years. Operating cost is calculated by summing the overhead operating fees, estimated resupply costs, regolith and slag transport costs, and electricity costs. The overhead cost is an estimated percentage of revenue.

This model was used to calculate values for an MVP plant (5,000 kg of oxygen per year), then to fuel one, three, and five SpaceX Starships per year. Results are summarized in table 5.3. For perspective, the 46.2 kW of thermal energy required for the MVP plant can be collected with a surface area of about two standard parking spots (6 m x 6 m). The solar collection area for one Starship of oxygen per year, however, is about 25 percent of an American football field.

Table 5.3. Scalability study summary

System Specifications	*MVP*	*1 Starship/year*	*3 Starships/year*	*5 Starships/year*
Oxygen production (ton/year)	5.0	155	465	775
Regolith required (ton/year)	20	620	1,860	3,100
Slag produced (ton/year)	15	465	1,395	2,325
Thermal power required (kW)	46.2	1,431	4,293	7,155
Electrical power (kW)	17.6	347.5	1,043	1,738
Electrical storage capacity (kW-hr)	522	5,220	5,220	5,220
Startup hydrogen required (kg)	28	330	502	655
Total system mass (ton)	*	98	294	490

*Removed proprietary data

There are three main revenue or value streams of the proposed system:[29]

- Sale of oxygen extracted from the lunar regolith. This serves primarily as LOX for propellent but also supplements the other two value streams.
- Energy storage through a fuel cell and water electrolysis unit. Electricity is purchased during the day from external vendors or generated directly from solar panels or waste heat. Electricity is sold at an increased price during lunar night to cover the purchase price during the day and energy storage hardware. Oxygen from the first value stream supplies the bulk of the reactant mass required for the fuel cell.
- Chemical recycling. Ingest waste from low-value process streams,[30] recombine, and re-sell the products.
    - Example 1. Methane ullage from a descent vehicle could be purchased, split, and combined with oxygen from the first value stream to make water. The excess carbon could be sold to a metals foundry (chapter 6).
    - Example 2. Oxygen and hydrogen could be sold to a fuel cell powered rover and water purchased in return.

The chemical recycling process stream can help balance supply and demand in the lunar economy and is an example of added value by secondary commercial products. **A key insight from LunA-10 is: Such secondary value streams can end up being key to a lunar commercial venture's profitability.**

The sale price of ISRU-sourced materials is initially expected to be driven by the launch costs to the lunar surface. Table 5.4 estimates prices for the main products of the LOPES Node.[31]

Table 5.4. Estimated current purchase and sale prices of commodities on the lunar surface

Commodity	*Estimated price*	*Rationale*
Sell oxygen	500-750 $k/kg	Based off a ~25% discount of landing cost
Sell slag	15-50 $k/kg	Estimate based on how much it costs to purchase regolith, robotic costs to remove, and added value of reduced metals
Sell lunar night electricity	20-30X daytime cost	Covers fuel cell use, electrolysis, re-liquification of oxygen, and storage of hydrogen
Sell water	500-750 $k/kg	Based off a ~25% discount of landing cost. Quantities limited based on methane/hydrogen supply
Oxygen/hydrogen rental	300 $k/kg	Rent hydrogen/oxygen for fuel cell use and accept it back in the form of water. Fee if not returned due to lost hydrogen. Assumes 1% of rental is lost.
Buy regolith	Market rate	Driven by supply and demand of RaaS vendors
Buy lunar day electricity	Market rate	Electricity needs to be sold cheaper than it costs to develop and ship panels from Earth
Buy communications	Market rate	Driven by supply and demand of communication vendors

As the scale grows, storing LOX becomes more power efficient. It takes 3.1 kW of energy to store 5 metric tons of LOX at the equator, but only about five times more energy (14.5 kW) to store 100 times more LOX (500 metric tons). Additionally, the storage becomes more resistant to power outages, as a higher thermal mass of the LOX will delay boil-off losses. However, as launch costs decrease, it takes longer for the ISRU plant to start becoming profitable. Eventually if launch costs were low enough, it would be cheaper to ship the required materials from Earth. Figure 5.5 shows the approximate relationship between launch costs and break-even time for the MVP- and Starship-sized LOPES Nodes.[32]

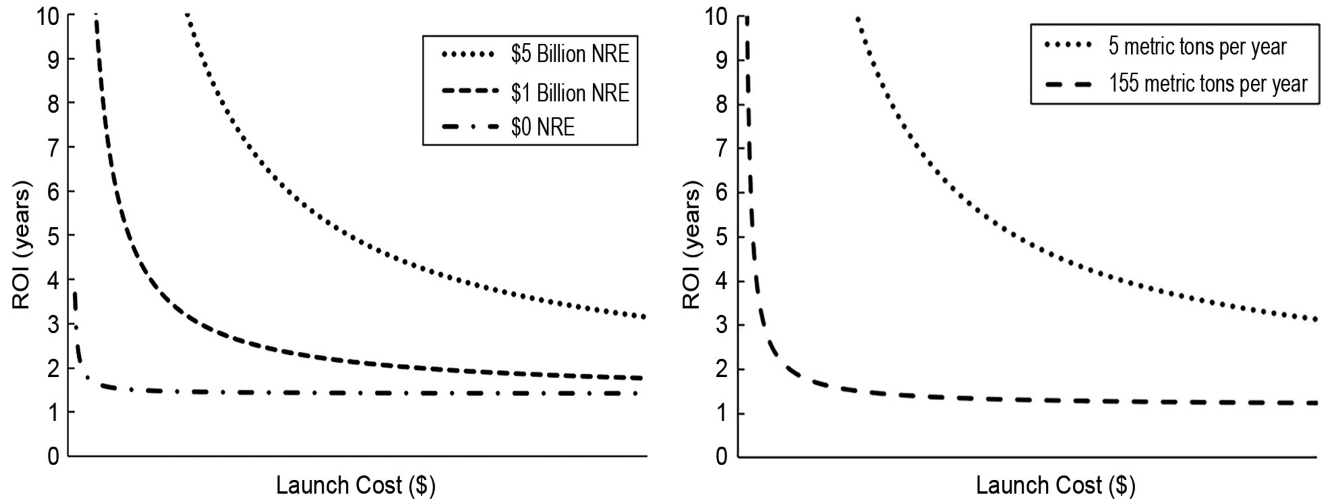

Figure 5.5. (Left) Break-even time as a function of launch cost and nonrecurring engineering (NRE) cost for an MVP plant (Right) Break-even time as a function of production capacity assuming $5B NRE. [Credit: Sierra Space]

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Hamo, Cohen, Stein, Schwartz, Walter-Range, and Itzkowitz are from Helios Project Ltd.
2. Caelus Partners LLC.
3. Authors White, Haggerty, Rogers, and Petrie are from Sierra Space.
4. Defense Advanced Research Projects Agency (DARPA).
5. Lunar regolith: the loose, unconsolidated material blanketing the lunar surface.
6. Guerrero-Gonzalez and Zabel, "System Analysis of an ISRU Production Plant."
7. Wilken, "SpaceX's Next Generation Space Transportation System."
8. Yan and Eng, "Solid Oxide Membrane Electrolysis."
9. Hu et al., "Mechanism in Surface Morphology of YSZ Ceramics."
10. Low-titanium mare soils contain (on average) 60.26% [O], high-titanium mare soils contain 60.30% [O], highland soils contain 60.82% [O], and KREEP soils contain 60.47% [O]. Sarantos et al., "Metallic Species, Oxygen and Silicon in the Lunar Exosphere." KREEP is an acronym built from the letters K (the atomic symbol for potassium), REE (rare-earth elements), and P (for phosphorus).
11. For example, higher concentrations of bronzite, ilmenite, and olivine can be achieved due to the iron and silicon content in these minerals. High-intensity magnetic separation can separate ilmenite (paramagnetic) from anorthosite (diamagnetic). Rasera et al., "Beneficiation of Lunar Regolith."
12. Zheng and Qiao, "Properties of Bulk Glass"; and Lim et al., "Microwave-Heated Lunar Simulants."
13. Iqbal and Moskal, "Recent Development in Advance Ceramic Materials."
14. For example, Phuah et al., "Ceramic Material Processing."
15. The 10-Year Lunar Architecture (LunA-10) program aims to study the rapid development of nonterrestrial technology concepts designed to move away from individual scientific efforts within isolated, self-sufficient systems and toward a series of shareable, scalable, resource-driven systems that can operate jointly, creating monetizable services for future lunar users in a mass-efficient manner. Many services are needed to field a commercial-owned and operated lunar infrastructure, and an underlying common framework that emphasizes integrated models of economic activity may be the "rising tide" that lifts all lunar vessels.
16. List price for an Astrobotic Commercial Lunar Payload Services lander (est. 2024), November 17, 2016, https://www.astrobotic.com/. See latest Payload User's Guide available at: "Astrobotic Lunar Landers: Payload User's Guide," Astrobotic, 2021, https://www.astrobotic.com/.
17. Roberts, "Cross-Program Design Specification."
18. McKay et al., "The Lunar Regolith," 296.

19. Standish et al., "Ceramics for Molten Materials Containment."
20. Thermal diffusivity α ranging from 1.04e-5 to 2.35e-5 cm2/s. Roberts, "Cross-Program Design Specification."
21. Yu, et al., "Getter Development for International Space Station Sabatier Assembly."
22. "Updated Datasheets," SunPower Inc., https://www.sunpowerinc.com/.
23. Burke et al., "Modeling Electrolysis in Reduced Gravity."
24. Heiken, Vaniman, and French, "Lunar Regolith," 296.
25. Meyer, "Lunar Petrographic," 47.
26. Li et al., "In Situ Investigations of Dust."
27. This simulant was selected by NASA as the closest chemical analog to the lunar highlands' regolith for carbothermal reduction testing.
28. Nickerson et al., "Global Lunar Regolith Depths Revealed."
29. More information on value streams specific to the Moon may be found in chapter 14.
30. Examples of low value process streams include ECLSS, propellant ullage, solar wind gases, CO2 based coolants, and fuel cell-based rovers.
31. Based on a cost of $1M/kg to the lunar surface.
32. Note that the $1B and $5B NRE presented here are examples to show the impact on investment return and do not represent the expected NRE costs to develop a Lunar Oxygen Production and Energy Storage Node. The 2024 launch costs are near the right side of the X axis; however, due to proprietary data rights limitations, the labels were removed.

6

Metal Ecosystem on the Moon

Regolith and Re-ISRU

Edited by Michael Nayak

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6.1 Introduction

Today, the cost to send even a single kilogram to the surface of the Moon has made mass efficiency a primary driver. Metal derived from in situ resources can play a crucial role in reducing reliance on Earth-based logistics. However, producing metal from lunar regolith requires a significant energy outlay, limiting the amount of metal that can be produced when early energy resources are constrained. **This sets the stage for the importance of a new concept explored under LunA-10, the concept of recyclable in situ resource utilization, or re-ISRU**.

The lunar community is accustomed to thinking about in situ resources as coming from regolith. But as the cadence of lunar landers sent to the Moon picks up, *they become part of the in situ environment*. This is particularly relevant to the current generation of landers that is not night survivable (e.g., IM-1 Odysseus, the first commercial lander to soft-land on the Moon). Such vehicles contain a large quantity of aerospace-grade metals and carbon, which are not native to the lunar surface. Can they be monetized and become part of a lunar value chain?

This chapter will explore the development of a space foundry, centered on a novel method for processing metals on the Moon. It is designed to transform lunar regolith into valuable metal products, paving the way for a sustainable industrial ecosystem in space. This foundry can accept aluminum and iron extracted from lunar regolith and output useful elements such as ingots, beams, wires, and sheet metal. More crucially, it can also accept scrap metal from other defunct lunar hardware. **Recycling this defunct hardware can become a new monetizable service for the lunar economy, particularly when each kilogram costs about $1 million to bring to the lunar surface.**

In situ metal-based products created by the foundry can be used for anything from robotic repair to building a lunar rail mobility system (explored further in chapter 12). Metal production on the Moon will be economically competitive in the early parts of the lunar economy, which is dominated by both high transport and hardware costs (fig. 6.1). As transport costs go down, improvements in hardware costs and process efficiencies will be required to remain competitive, but there will also be increased demand (e.g., ten times more metal mass to expand a lunar rail).

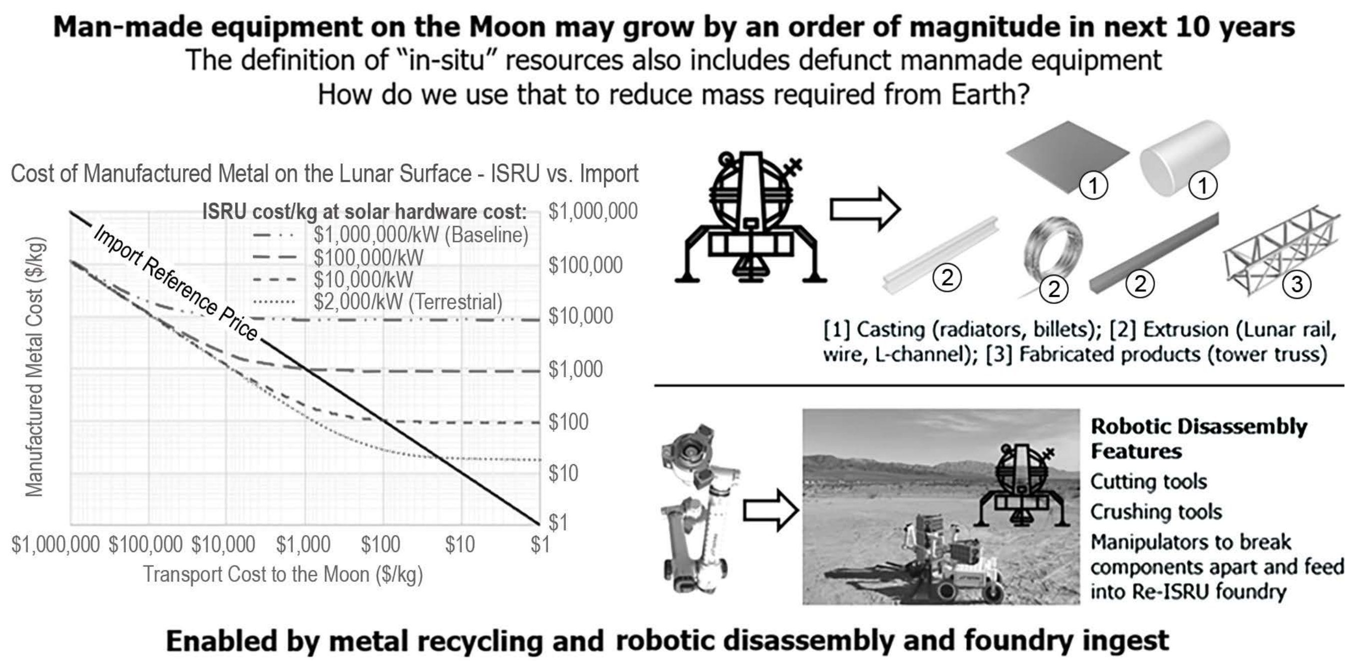

Figure 6.1. Why metal recycling matters: Man-made equipment on the Moon may grow by an order of magnitude over the next decade. A new definition of "in situ" resources includes defunct man-made equipment. How can this equipment reduce the mass required from Earth? [Credit: CisLunar Industries, GITAI]

6.2 Framework Overview

CisLunar Industries has been developing a metal-forming Modular Space Foundry (henceforth: foundry) that can ingest metal and cast it into metal-based products in microgravity. The design and results of this are available in the literature,[8] and the underlying physical principles are described in the *Handbook of Space Resources*.[9]

This chapter explores key constraints, opportunities, and product demands that will ultimately drive the requirements for this or other metal foundries. The foundry is designed as a modular system with a common interface and unit size. Each module represents a step in the metal processing chain and can be removed, added to, or replaced to support repair, expansion, or reconfiguration. The pilot plant is designed to accept stock material (e.g., a portion of a lunar lander) with maximum dimensions of 0.5 m x 0.2 m x 0.2 m and can then be scaled to greater sizes. Two primary framework views were researched and created. The first summarizes the metal and metalloid infrastructure value chain.[10] This framework offers many unique opportunities to integrate into a future commercial infrastructure. Benefits range from simple down-mass savings to large-scale physical infrastructure elements too large to be practical without using in situ resources.[11] Key steps within this value chain are outlined below:

- Prospecting: A partner surveys, drills, and samples the lunar surface to identify the highest quality and most accessible resources. Self-sustainability and commercialization become feasible as infrastructure matures.

- Extraction and beneficiation: A partner collects regolith and beneficiates it using low-energy methods to yield higher purity smelting inputs, resulting in streamlined refinement with significant downstream energy savings.
- Mobility: Regolith is transported from the extraction site to the manufacturing hub, beginning with the smelting node, where regolith is deposited in a storage facility.
- Smelting: Processed regolith undergoes separation processes, such as MRE (molten regolith electrolysis, section 5.2.1). Depending on the power supplied, metal products with different material properties can be made.
- Foundry: Consists of modular subsystems. The system receives processed metal from regolith or recyclable materials (including waste or worn materials from maintenance), which is transported into the furnace system. Metal is melted and formed to a desired shape in one of several selectable shaping systems. Material properties may also be modified through alloying or fillers.
- Mill: Milling enables refinement of cast foundry products into additional shapes and properties. Secondary processes such as extrusion and drawing occur, which improve mechanical properties for products such as wire and structural components. Aluminum and iron products may also be hot or cold worked to produce complex shapes with engineered mechanical properties.
- Factory: In later stages of development, higher complexity and precision manufacturing may be accomplished by building additional nodes on, or exporting from, the foundry and mill nodes. This could include metal 3D printing, multi-step construction, assembly through robotic manipulation, and more.

The second framework centers around how the foundry/mill portion of the metal value chain could serve the activities of other lunar economy contributors. The other companies in the LunA-10 consortium were used as representative examples, as shown in figure 6.2. The key interfaces are the following:

- Maintenance infrastructure: Metal manufacturing nodes prioritize high availability with a "design for maintainability" strategy. Replaceable wear components are produced in situ using recycled or mined materials. The modular system design includes Internet of Things (IoT)–driven diagnostics, predictive maintenance, and line-replaceable units.
- Rail product: By manufacturing specialized transit cars and rail infrastructure, extraction efficiency can be improved in areas with challenging terrain or far-apart resource deposits.
- Oxygen product: While not a core product of the metal framework, oxygen is the byproduct of ISRU metal extraction with multiple commercial applications.
- Lunar standard and other manufacturing nodes: The billets, beams, rails, and blocks produced from this step can be exported to allow further manufacturing by future customers.

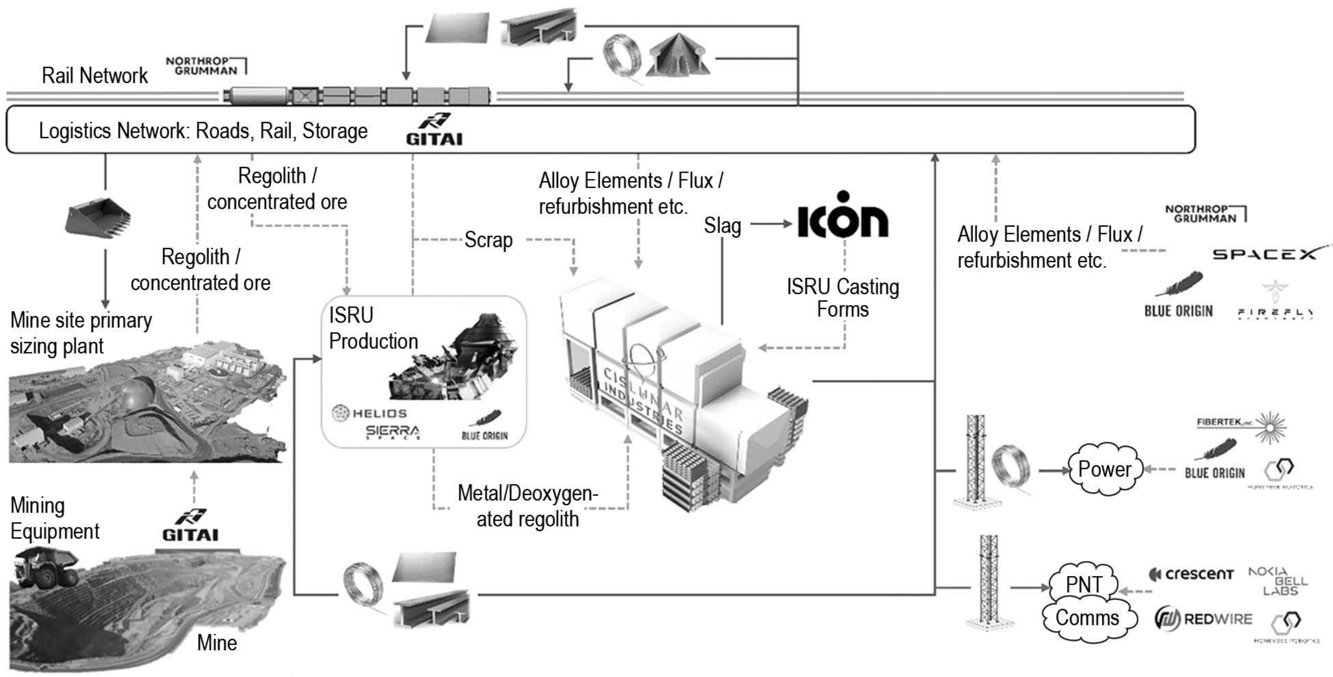

Figure 6.2. Summary of the foundry framework, highlighting external dependencies to other lunar commercial services.

6.3 System Overview

Due to the logistical difficulty and economics involved in launching large masses from Earth, the process design is based around maximizing resiliency and versatility. A modular design with standardized interfaces allows system upgrades at lower cost, lower risk, easier maintainability, and simplified configuration changes.

The first production system will focus solely on the core capabilities required to ingest feedstock and output a product. It is composed of the following modules:

1. Shredder module. Allows for nonstandard feed sizes and form factors to be processed into smaller shreds and reduce upstream unpredictable behavior.
2. Material system. Input material transported throughout all stages of the foundry process.
3. Input module. A pressurized material storage area facilitates transfer of roughly processed input materials while reducing pressurization losses in handling.
4. Melt/batch casting module. Roughly processed material is introduced into the crucible of the melting system and batch cast into billets.
5. Extrusion module. Roughly standardized billets are fed into the extruder module and die-extruded into the desired profile shape.
6. Wire drawing module. Cast billets or extruded rods are converted to iron/steel wires through wire drawing.
7. Heat treatment. Final material crystal structure is controlled through a finishing heat treatment stage.
8. Inspection/output module. The other end of the pressurized system from the input models.

The expected inputs and outputs of the foundry are summarized in table 6.1 below.

Table 6.1. Lunar foundry inputs and outputs

Inputs into the system	*Output from the system*
Recycled material	Billets (aluminum/steel, cast)
ISRU metal	Rail (aluminum, extruded)
Regolith	Mining tools (steel, cast)
Power	Towers (aluminum, extruded)
Data	Radiators (Si/Slag, cast)

Some of the limitations of the foundry are summarized in table 6.2 below.

Table 6.2. Lunar foundry anticipated limitations

Limitation	*Explanation*
Efficiency dependent on material conductivity	Induction heating works on conductive materials only. Nonconductive materials can be heated using conductive sleeves (such as graphite), but heating efficiency will be reduced.
Partial atmosphere required	The melt/casting process requires a small amount of pressurization to its environment to ensure metal alloy elements do not boil off fractions. Any casting operations are limited by the maximum sealed volume of the system.

Using reference numbers for the mass and power of these eight stages, specific power and flowrate metrics are derived for a parameterized sizing of each module. This is used to scale the required system mass to a desired maximum system flow rate. For a desired pilot plant flow rate of ~90 kg/hour, a collective mass of 5,640 kg and a collective power requirement of 100 kW is found (fig. 6.3).

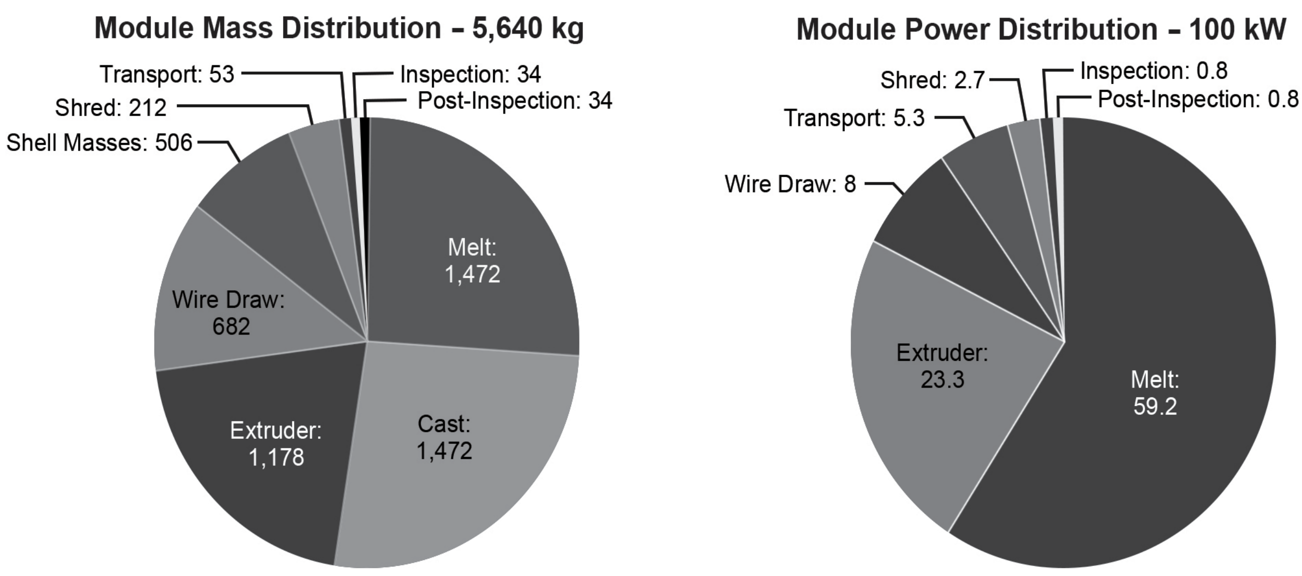

Figure 6.3. Pilot foundry mass and power across modules. [Credit: CisLunar Industries]

The resulting pilot foundry outputs are split into three main production categories, with example products listed below:

- Cast Products
    - Castings. Products produced using molds intended for direct use without additional forming. Examples include iron/steel tooling for mining and construction operations and fixtures for assemblies such as a lunar railroad.

- Plates. Cast plates could be used for thermal control or impact protection for infrastructure customers. As the structural properties of these items are not critical, these components could be made with inputs that otherwise would be discarded from regolith extraction and Re-ISRU processes.
- Billets. The prerequisite product needed for further processing systems. Multiple diameters of billet can be cast to optimize processes, if needed.

- Extruded Products
  - Lunar rail (extruded aluminum). Used by transport infrastructure companies to transport everything from raw ore materials to products.
  - "L" channel (extruded aluminum). Used for structural components and tower construction due to rigid and lightweight form. Two L-channel extrudes can be welded together to create the box-section profile for simpler structures, such as those used in small communications towers and line-of-sight wireless power transmission.
  - Wire (extruded aluminum, drawn iron/steel). Used for power transmission and in situ printing of complex parts. Versatile wire-fed additive printers can print parts that otherwise could not be made by subtractive manufacturing.
  - Reinforcement bars (drawn steel). Drawn steel wires and rods to be added to landing pads and other sintered/cast regolith structures to reinforce these structures and substantially reduce the amount of regolith processed.[12]
- Fabricated products. Base units welded together to form larger structures of customizable height and configuration:
  - Monopole towers. Communication/power towers (wired and wireless). Constructed from either two or four extruded L-channel profiles to create a box tube structure. These can be used for towers of less than 15 m in height.
  - Lattice towers. Communication/power towers (wired and wireless). Constructed from extrusion and cast products, welded to form lightweight, rigid structures for heavier payload or greater height than monopole structures.
  - Wire rope. Mining equipment, cranes. Assembled from multiple drawn steel wires providing cables of high strength and flexibility.

6.4 Process Energy Modeling

Energy and power consumption will be a key driver for the production capacity and operating costs of the early metal economy. A set of system models was developed to estimate total energy costs. These models provide an estimate of energy consumption for processes such as casting, forming, and fabrication as well as upstream processes such as mining and metal extraction from regolith. The models represent order of magnitude estimates for scaling discussions and are intended to be refined as system knowledge is improved. The aim is to minimize peak power demand to consequently reduce the mass of the power supply system required.

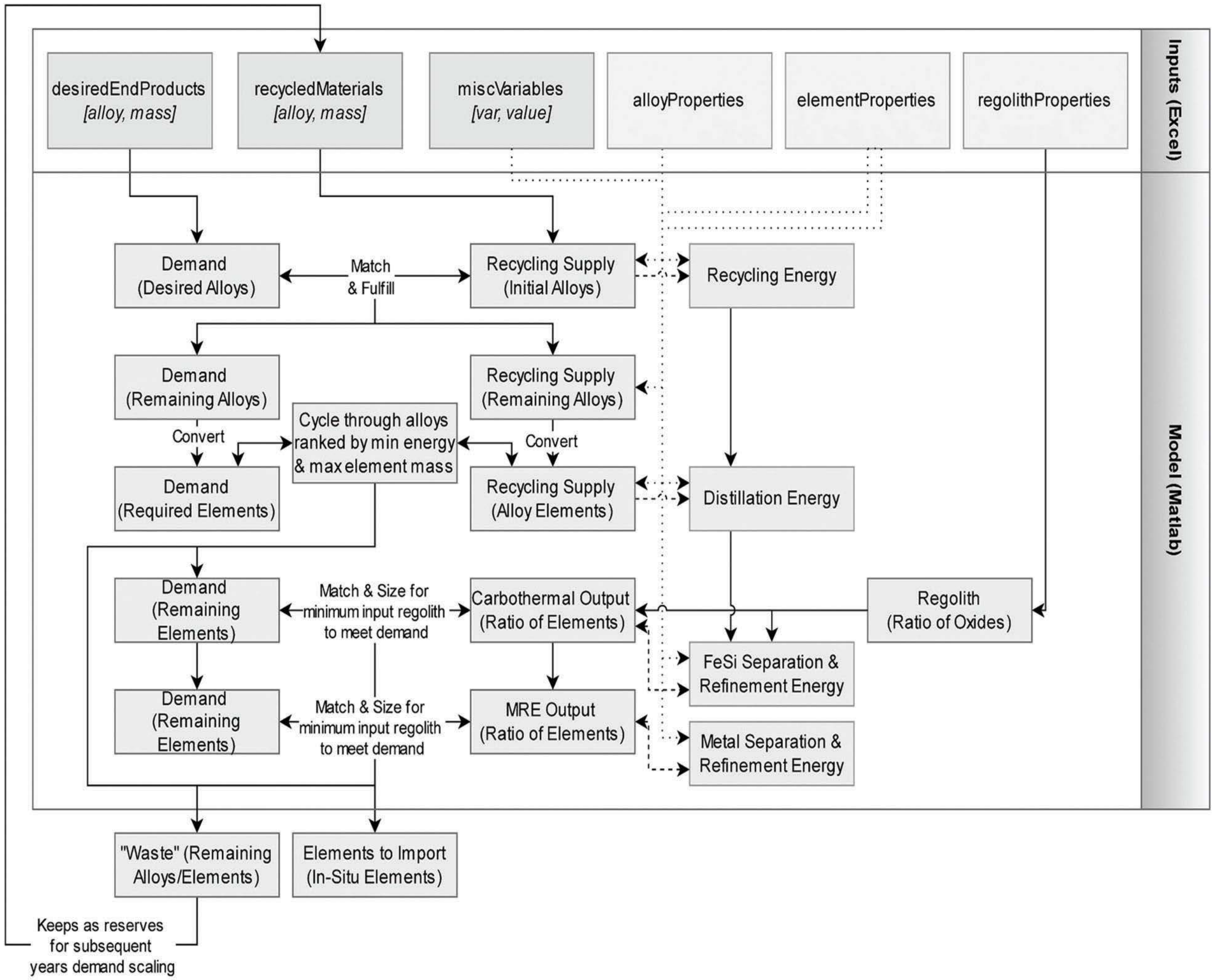

Figure 6.4. Metal framework energy-mass model. [Credit: CisLunar Industries]

This model first assumes available recycled materials, with matching alloys to meet demand, before distilling recycled alloys into their constituent elements for new alloy creation. If recycled elements alone do not meet demand, the model next relies upon separating and processing metals from the regolith to meet demand. The remaining trace elements that cannot be produced in situ are then estimated for import from Earth. Any leftover material produced is added as a reserve for future scaling. Model estimates for architecture-level energy required before manufacturing are detailed in figure 6.4.

6.4.1 ISRU Extraction and Refinement

The most immediately available upstream source of metal comes from carbothermal reduction of regolith for oxygen production (section 5.3). The byproduct of this oxygen production is deoxygenated regolith (DOR) containing metallic iron and silicon, along with remaining metal oxides from the regolith feedstock. Back-calculating from numbers provided in chapter 5, DOR requires roughly 8.8 kWh/kg to produce.

To refine this DOR into iron for manufacturing, the ferrosilicon is first separated from the remaining oxides through soft-crushing and particle sorting. This leverages the relative brittleness of metals (versus oxides) and requires fractions of a kilowatt of power. After sorting, fractional freezing separates the iron from the liquid. The precise outcome depends on the ratio of silicon and iron, with multiple possible phase chemistries and intermediate compounds.

Assuming highlands regolith and an energy-optimum 20 percent O2 (mass) extraction from the regolith,[13] the output DOR is approximately 10 percent Fe, 19 percent Si, and 71 percent oxides. Assuming the oxides can be successfully separated through the soft-crushing method, the base refinement energy is ~2 kWh/kg-iron. A value of ~3 kWh/kg is assumed to add margin for thermal losses and soft crushing.

Differing iron yield and bulk processing regolith makes energy metrics highly sensitive to regolith composition. Iron, for instance, varies between 2 percent and 11 percent mass and aluminum between 7 percent and 13 percent mass, depending on the lunar region. The relative inverse correlation of iron and aluminum weight gives rise to differing favorability of elements in energy calculations.

Secondary reduction reactions can be used to increase the relative yield of iron. This increases iron yield relative to DOR processing in highland regions by a factor of 20 for minimal additional energy input. Because iron concentration is so low in highland regolith, significant further gains can be realized through even moderate beneficiation to concentrate the ore.[14]

With iron and silicon from the DOR separated by the processes above, the resulting byproduct yields a concentrated mixture with reduced weight of SiO_2 and increased weight of Al_2O_3, MgO, TiO_2, and CaO_2, an attractive option for further reduction of the remaining metal oxides into favorable engineering metals.

Energy calculations use the process below, where $[m_{metalDemand}]$ is a matrix of elemental demand for the elements found in regolith and $[R_{metalRegolith}]$ is a matrix of the ratio of elements produced from regolith. These matrices are divided elementwise to derive the required regolith mass to produce each element. The limiting element represents the amount of regolith to be processed to meet the overall demand.

$$m_{regolith} = max\left(\frac{[m_{metalDemand}]}{[R_{metalRegolith}]}\right)$$

The mining energy required in terms of the specific energy of mining and transportation, q_{mining}, is calculated as:

$$E_{mining} = m_{regolith}\, q_{mining}$$

To calculate the smelting energy, two equations incorporate the complexity of reactor design and thermal losses.[15] The total oxygen mass produced is calculated by multiplying the ratio of oxygen mass separated from each oxide in the regolith utilizing a separation efficiency, the mass ratio of that specific oxide in regolith, and the stoichiometrically calculated mass ratio of oxygen in the oxide:

$$m_{O_2} = m_{regolith} \sum_{i}^{n_{oxides}} n_{sepEff}\, R_{oxide_i} \frac{n_{Oi}\, M_O}{M_{oxide_i}}$$

$$E_{smelting} = m_{O_2}\, q_{O_2}$$

In the smelting process, DOR exists as a bulk of mixed metals to be separated through a refinement step. To simplify the number of production steps, a vacuum distillation process separates high-quality metals in bulk. Alternate chemical processes would likely decrease overall energy, such as partial bulk vacuum distillation followed by carbonyl reactions to efficiently target each desired element.

The vacuum distillation energy estimate is calculated separately for each element being distilled. This includes the energy to raise the element's temperature from the starting temp to the melting point ($q_{preMelt}$), the heat of fusion of the element to melt it (h_{melt}), the energy to raise the element from the melting point to the boiling point ($q_{preBoil}$), and the heat of vaporization of the element to boil it (h_{boil}). Including an efficiency metric to calculate the specific distillation energy, $n_{effDistillation}$, the distillation energy for an element is calculated as:

$$q_{distillation} = \frac{(q_{preMelt} + h_{melt} + q_{preBoil} + h_{boil})}{n_{effDistillation}}$$

$$E_{distillation} = m_{element}\, q_{distillation}$$

The overall distillation energy is calculated by summing the distillation energies of all the constituent elements.

Within distilled elements, desired products exist in the form of alloys, with a base element followed by several constituent elements at different ratios. For instance, Aluminum 6005 is composed of 98.7 percent aluminum, 0.8 percent silicon, and 0.5 percent magnesium. Together these define the metal mass required from regolith and the metal mass elements required from import. Regolith properties and processing energy inputs are presented in table 6.3.[16]

Table 6.3. Regolith properties and processing energy inputs

Property	*Energy Input*
Regolith's solid heat capacity	~1200 J/kg
Regolith's liquid heat capacity	~1550 J/kg
Regolith melts	~1600 K
Regolith's latent heating of melting	~465 kJ/kg
Smelting energy	~31.6 kWh/kg-O_2
Smelting temperature	2000 K
Mining and transport specific energy	~0.5 kWh/kg (Conservative estimate)
Reference: Terrestrial mining and transport specific energy	~0.3 kWh/kg (Aluminum)[17]

These equations are used to calculate extraction and refinement energy for desired quantities of specified materials and to calculate overall system energy requirements as product demands increase (section 6.6). Additionally, a set of baseline values is calculated to explore total ISRU power consumption for the following mixes of material demands at full foundry capacity: (1) aluminum products only; (2) iron products only; (3) 50/50 split by mass between aluminum and iron; and "ideal" cases for (4) aluminum and iron; (5) aluminum and magnesium; and (6) aluminum, iron, magnesium, and titanium.

These cases represent various scenarios of metal demand, where "ideal" cases represent the most energy efficient mix of the given metals. Magnesium and titanium are shown as reference for future consideration but are not covered further here. Additional elements such as silicon will have use for alloying and eventually crystal fabrication, but this is expected to be a small fraction, with minimal impact on the energy balance.[18]

6.4.2 Production Process Energy Calculations

Production processing energy for terrestrial fabrication of aluminum products typically accounts for 2.5 percent to 5 percent of overall energy cost, with the remainder primarily consumed in extraction and refinement of the metal.[19] This ratio is expected to be lower in the lunar ISRU case, particularly for aluminum, as its concentration in the regolith is lower than terrestrial, metallurgical-grade bauxite ore. The production process estimates are therefore not expected to affect product price significantly, based on analysis assumptions that impact material input costs. These equations are developed as a first-order approximation based on theoretical energy requirements, with estimates for mechanical and thermal efficiency.

A large portion of processing energy is consumed by heating. Significant energy savings can be realized by first optimizing the system to eliminate cooling and heating cycles, then reclaiming heat where possible. Examples are transferring billets from casting to extrusion while hot or using a heat pump system to transfer energy from a finished product to preheat materials for casting. This savings is accounted for by a heating factor applied to all heating energy calculations.

Specific energy of casting is calculated based on the specific energy required to raise the desired metal to its target casting temperature, plus heat of fusion for the material:

$$\dot{E}_{Cast} = HF * (C * (T_{cast} - T_{initial}) + \Delta Hf)) * \eta_{heat}$$

where HF is the heat recovery factor, η_{heat} is the heating efficiency of the furnace, T_{cast} and $T_{initial}$ are the casting and initial temperatures, C is the specific heat capacity of the metal, and ΔH_f is the heat of fusion.

Specific energy of extrusion is calculated based on extrusion force and extrusion ram travel:[20]

$$\dot{E}_{xtr} = (C * (T_{cast} - T_{initial})) * HF * \eta_{heat} + F_{extr} * s_{ram} * \eta_{mech}$$

where $A_{profile}$ and η_{mech} are the heating and mechanical efficiencies, F_{extr} is the extrusion force, and s_{ram} is the ram travel per kg of extruded profile:

$$\dot{s}_{ram} = \frac{1}{A_{profile} * \rho * R_{extr}}$$

where $A_{profile}$ is the area of the profile, ρ is the material density, and R_{extr} is the extrusion ratio of the profile.

Wire drawing energy is primarily driven by the mechanical energy required to deform the wire. This would be provided by an electric motor for reasonably high process rates, although hydraulic-driven systems are used on Earth for low-throughput applications. Total drawing energy for a member of drawing passes is a product of drawing force and wire length leaving the drawing die:

$$E_{draw} = \eta_{mech} * \sum L \cdot F_{draw}$$

where η_{mech} is the mechanical efficiency, L is length of wire after drawing for each pass, and F_{draw} is the force required to draw the wire:

$$F_{draw} = \bar{\sigma}_f Af ln \frac{A0}{Af}$$

where $\bar{\sigma}_f$ is the average flow stress of the material, and A_0 and A_f are the initial and final wire cross-sectional area respectively. Average flow stress can be calculated as:

$$\bar{\sigma}_f = \frac{K\epsilon_1^n}{n+1}$$

where K is the strength coefficient, ϵ is the true strain, and n is the strain-hardening exponent. A low-carbon steel was used as a baseline case with a K of 530 megapascals (MPa) and n of 0.26.[21] Frictional and redundant work losses were estimated at 0.4.

The maximum theoretical reduction during a single wire drawing pass occurs when the total stress across the cross section (A_f) equals the material's yield stress. This is ~63 percent reduction for non-work hardening materials. In practice, most operations utilize much lower per-pass reduction rates (~20 percent) to account for frictional losses, reduce die wear, and reduce the risk of failure from localized imperfections acting as stress concentrators. Annealing, a recrystallizing heat treatment, eliminates dislocation buildup during work hardening and softens the material between drawing passes. Wire drawing enables the forming of most ductile metals, even from iron-based alloys that are difficult to extrude.

Heat treatment energy is expected to be provided through waste heat capture from higher temperature processes such as melting and therefore assumed to be zero.

Heat treatment water requirements. Some heat-treated parts will greatly benefit from rapid cooling by quenching. Water is used as a quenching fluid because it will likely be available from ISRU processes. Quenchant can be reused by cooling and filtering the fluid. The high-carbon steels proposed for use as ground-engaging equipment and mining tools substantially improve in hardness and strength when quenched and tempered. Mass of water to quench a part is as follows:

$$m_{H_2O} = m_{Fe} \frac{c_{p-Fe} \cdot \Delta T_{Fe}}{c_{p-H_2O} \cdot \Delta T_{H_2O}}$$

where m_{Fe} is the mass of the steel part, ΔT is the change in temperature, and c_p is the heat capacity of the material. For a high-carbon steel part, the starting temperature of the heat treatment will be 850°C.

6.5 Economic Modeling

On Earth, the market is driven by supply and demand. With this detailed understanding of production processes and associated energy and power costs, we can begin to analyze the economics of various aspects of metal production. This incentivizes optimization of product manufacture for cost. On the Moon, the market does not currently exist, so this dynamic is skewed from a lack of demand data.

As a supplier, one may determine the baseline economics of lunar production by calculating costs associated with production and scaling this to varied production levels. A primary cost driver is the high transportation costs per unit mass, including resourcing stock materials, hardware for additional processing equipment, and replacement of wear components such as molds and dies. Therefore, efficiency is likely driven by simplicity and reuse of products. This chapter will establish an initial selection of products that can be economically fabricated using a pilot plantscale foundry.

Pilot products are explored through case studies; these case studies covered systems with a high mass fraction and reviewed how they could be functionally replicated with relatively simple product alternatives produced through in situ metal forming processes. Additionally, it was considered how these simple product profiles could be adapted or combined using fabrication methods, such as electron beam welding and cutting, into more complex assemblies.

Baseline costs are calculated using the currently advertised CLPS mission costs of \$1M/kg.[22] At this cost, minimum product prices may not produce sufficient demand to recapitalize the system. A *reduced* transportation cost of \$50,000/kg is also used to estimate costs with future heavy-lift landers such as SpaceX's Starship.

Energy costs are calculated based on values for solar hardware cost and efficiency in the literature, for both the baseline and reduced transportation costs.[23] For transport and energy, cost factors (CF_T, CF_E) are calculated as the ratio of the reduced to baseline cost.

$$\varepsilon_{avg} = \varepsilon_{solar} * SolarAvailability$$

$$C_E = \left(\frac{C_T}{\varepsilon_{avg}} + C_{HW}\right) \div AmortizationPeriod$$

$$CF_T = \frac{C_{T-reduced}}{C_{T-baseline}}$$

$$CF_E = \frac{C_{E-reduced}}{C_{E-baseline}}$$

These equations are used to evaluate the sensitivity of costs to transportation and solar hardware costs.

The foundry requires external commercial services, presenting an example of how commercial services are a node in a larger economy, with both input and output dependencies (fig. 6.2). Recyclable or regolith input to the foundry is assumed to be provided by commercial Robotics as a Service (RaaS). As discussed in chapter 8, RaaS prices primarily scale with transportation costs. RaaS costs using baseline transport costs are therefore scaled by the transportation cost factor:

$$C_{RaaS} = C_{RaaS-baseline} * CF_T$$

Material inputs will consist of ISRU, recycled, and imported metals. ISRU metals will be refined from DOR, a secondary product from ISRU oxygen production (section 5.2.2). The cost of these materials is driven primarily by energy costs and therefore scales by the energy cost factor.

$$C_{ISRU} = C_{DOR-baseline} * CF_E$$

Recycled materials will be primarily sourced from scrap materials; cost is estimated by applying a scrap cost factor to the value of a refined metal product. The actual value of refined metal products depends on market forces that cannot be predicted at this time; this cost will be estimated based on the average cost/kg. Imported materials cost is assumed to be equal to the reduced transportation cost used in this analysis. Cost of the imported material itself is assumed to be negligible relative to the transport cost.

$$C_{Recy} = C_{ISRU-avg} * CF_{scrap}$$

$$C_{import} = C_T$$

Product price P_{prod} is based on the alternative cost of transporting an equivalent product from Earth. This price is adjusted proportionally for relative value based on mass differences if the Earth-sourced equivalent could be made from a lighter material or otherwise be mass optimized, differences in service lifetime, and fixed cost differences such as added setup costs. Finally, the price is reduced by a market-incentive factor, which is intended to stimulate demand under high transport costs but will be phased out as transport prices decrease. In summary, product price is defined as:

$$P_{prod} = (m_{prod} * C_T * Adj_{value} + Adj_{fixed}) * MarketIncentive$$

where m_{prod} is the mass of the product, Adj_{value} is the proportional value adjustment, and Adj_{fixed} is the fixed price adjustment.

Deployment costs for a system are calculated based on hardware fabrication, site preparation, delivery, and required robotic services. System hardware costs are largely driven by capabilities chosen as part of this study and will therefore not be calculated in detail. A rough order of magnitude estimate is developed based on legacy space hardware systems with similar levels of complexity. Site preparation will consist of grading and preparing a pad surface for the foundry, the cost of which will be determined by a regolith sintering service provider (see chapter 9 for details). Delivery costs are calculated based on the expected mass of the foundry and anticipated transportation services cost, plus estimated launch insurance cost (chapter 21).

Recurring costs are based on estimates for ground operations, maintenance, RaaS for material loading/unloading, power consumption, and material inputs. Ground operations are based on expected mission control operators, overhead to cover facilities, and post-launch mission insurance. Maintenance costs are based on transportation of expected replacement components and associated RaaS time for servicing.

Table 6.4 lists the estimated transportation and energy costs based on these calculations:

Table 6.4. Estimated costs for key foundry inputs

Input	*Baseline*	*Reduced*
Transportation	$1M/kg	$50k/kg
Energy	$308/kWh	$37/kWh
RaaS-Rover	$40,000/hr	$2,000/hr
Raas-Arm	$20,000/hr	$1,000/hr
DOR	$16,000/kg	$1,926/kg

Examples of calculated product values are shown in table 6.5.

Table 6.5. *Product pricing examples*

Product	*RASSOR Mining Tooth, set of 32*	*Rail, per m*	*Additive Mfg. Feedstock, per kg*	*25m Tower, each*
Mass, kg	1.28	3.5	1	125
Value Adj	0.5	0.8	1	0.5
Fixed Adj	0	0	0	0
Incentive	0.8	0.8	0.8	0.8
Price	$25,600	$112,000	$40,000	$2,500,000

Value adjustments are determined as follows:

1. ISRU RASSOR[24] mining teeth would be fabricated from high-carbon steel and are approximately four times heavier than the aluminum teeth they replace; however, they are expected to last twice as long.

2. Additive manufacturing feedstock is expected to be effectively equivalent to terrestrially produced feedstock. An adjustment factor of 1 is therefore used.

3. ISRU rail and ISRU towers will likely be slightly heavier than their terrestrially produced equivalents due to material and processing limitations. A value adjustment of 0.8 is assumed for lunar rail and 0.5 for towers.

Considering this, estimated deployment costs for a 500-ton annual capacity foundry at $50,000/kg transport costs are shown in table 6.6.

Table 6.6. Estimated deployment costs of foundry system

Deployment Phase	*Cost*
System hardware	$250,000,000
Site prep	$825,000
Delivery	$302,000,000
Installation	$79,400
Total	$554,000,000

Estimated recurring costs for a 500-ton annual capacity foundry producing aluminum and iron, at cost-optimized production ratios, are shown in table 6.7.

Table 6.7. Estimated recurring costs at 500-ton annual foundry production

Aspect	*Cost*
Ground operations	$9,700,000
Maintenance	$2,300,000
Robotic services	$132,000,000
Power consumption	$1,300,000,000
Material inputs	$4,200,000,000
Average cost per kg	$11,000

For ISRU extraction and refinement, results of the baseline energy cases are shown in table 6.8. "Iron only" is the most energy efficient case, due to the low energy, high yield potential of silicon reduction refining. The nominal Al-Fe mix yields a ratio of roughly 7 kg of iron for every kg of aluminum, with 16 percent higher average energy consumption. An even split of iron and aluminum consumes 175 percent more energy, and aluminum-only consumes over 750 percent more energy.

Table 6.8. Average energy requirements for metal inputs at various demand cases

Demand Case	*Fe Only*	*Al-Fe-Mg-Ti Ideal*	*Al-Fe Ideal*	*Al-Fe 50/50*	*Al-Mg Ideal*	*Al Only*
Mass, ton	500	57,398,396	63,437	250,250	300,200	500
Regolith, ton	17,570	11,153	12,267	7,011	1,867	4,340
Mining, kWh	8,785	5,576	6,134	3,505	934	2,170
Extraction, kWh	1,210	4,314	4,745	16,125	25,258	58,710
Refinement, kWh	0	1,754	1,929	7,712	11,851	27,546
Total, kWh	9,995	11,644	12,808	27,343	38,042	88,426
Total, kWh/kg	20	23	26	55	76	177

Finally, production process energies are calculated in table 6.9.

Table 6.9. Extrusion energies calculated for example profiles

Profile	*Material*	*Profile Area (mm2)*	*Heating Energy (kWh/kg)*	*Forming Energy (kWh/kg)*	**Specific Energy (kWh/kg)**	**Energy per meter profile (kWh/m)**
Rail	6063-T5	1290	0.230	0.012	**0.404**	**1.413**
40x3mm "L" channel	6063-T5	231	0.230	0.014	**0.406**	**0.253**
80x4mm "L" channel	6063-T5	624	0.230	0.016	**0.410**	**0.693**
5mm wire	1100-O	79	0.230	0.019	**0.249**	**0.013**

The economic model (fig. 6.6) shows the production cost for several scenarios of energy cost scaling with transportation cost, relative to the reference price of importing materials from Earth. This chart shows a "zone of viability," where products can be sold at a positive margin: the area between the cost of making the products and the maximum price of the product at the import reference price.

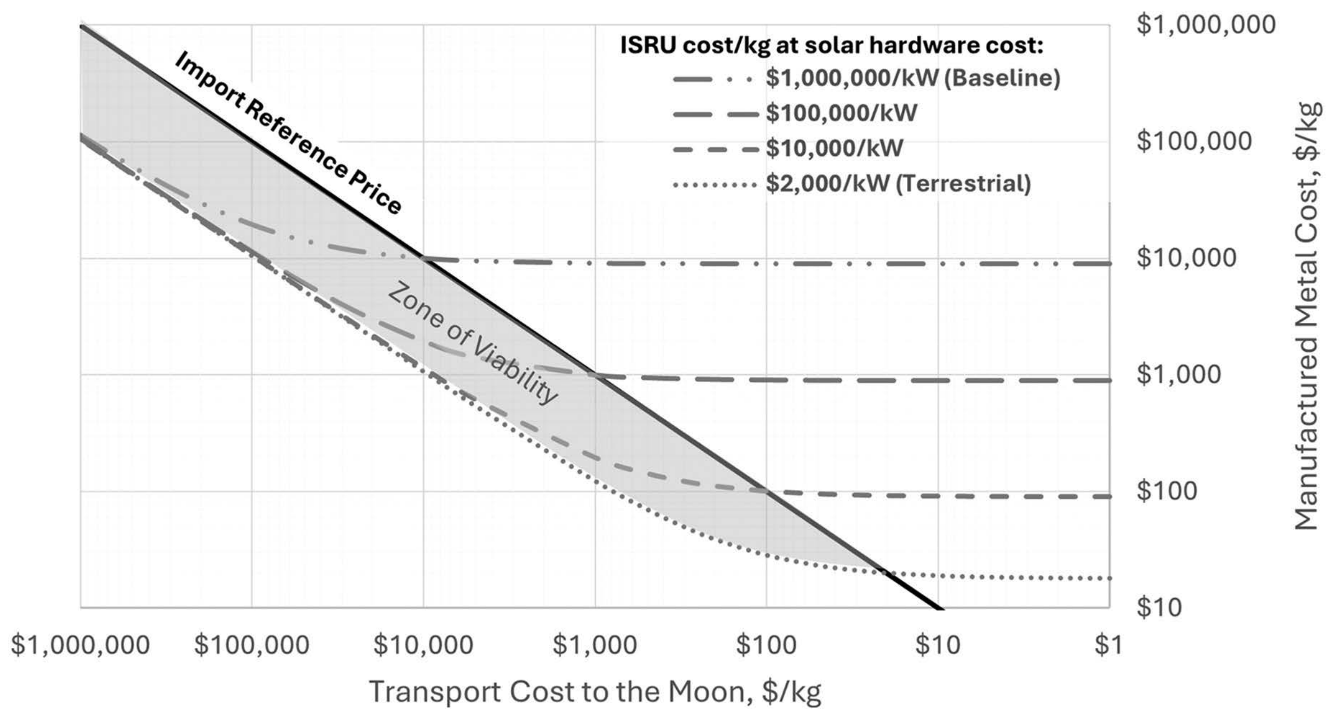

Figure 6.5. Cost of manufactured metal on the lunar surface, ISRU vs. import. [Credit: CisLunar Industries]

Based on current assumptions, energy costs down to approximately $10,000/kg are primarily driven by transportation costs to deliver solar hardware to the Moon. Below this, power costs are driven primarily by solar hardware costs, currently assumed at $1M/kW. The high cost of power hardware is primarily driven by the low build quantities and the need to maximize efficiency and reliability. A reduction of transportation costs would drive a shift toward commoditization of systems and relaxing efficiency and reliability requirements. Terrestrial systems exist robustly at ~$2,000/kW, signaling dramatic room for improvement.

As power unit costs go from $1M/kW to $2,000/kW (see chapter 4 for a discussion on lunar power scaling), the break-even point for importing material vs. ISRU production drops from $10,000/kg to $20/kg. Improvements in prospecting, beneficiation, and process efficiency will further reduce ISRU metal production costs. A drop in transport cost also allows for an increase in launch frequency, utilization of the Moon, and demand growth for foundry systems that can be operated at decreased cost.

6.6 Scaling Study

A scaling study was conducted to iteratively drive the optimal sizing and economics of the metal ecosystem. Ideally, this would in turn reduce the cost of deployment for future additions. As with Starship for oxygen, the pacing demand case for in situ metal is a future lunar rail, discussed further in chapter 12. Therefore, metal ecosystem scaling is based on the demand for a network of power lines, materials to support ISRU operations and heat rejection such as radiator panels, and rail systems.

Using the length of wired power transmission required as a case study, demand figures can be fed into the ISRU extraction model to determine energy requirements, which can iteratively feed demand for solar tower structures (discussed further in chapter 10). The overall power demand can also be used to estimate total radiator capacity need for thermal rejection, assumed at 25 percent of total power needs. For tower scaling case calculations, a 25m single-extruded box tower is assumed, resulting in ~200kg of payload for photovoltaics with a literature average peak specific power at ~7.5 kg/kW, which is then reduced by an estimated 25 percent to not repeat structural mass. It is assumed that this configuration can achieve ~80 percent yearly sun exposure, resulting in a ~3,000 kWh/yr/kg-structure created in situ.

The nominal scaling case assumes aluminum as the base metal for fabrication of the Lunar Rail Network. The silicon reduction process for iron extraction, however, can significantly decrease the ISRU energy cost of iron relative to aluminum. Because of this, a second scaling case is presented that uses iron as the base metal for rail network construction. This can be used to quantify the potential benefits of switching to iron for rail production.

Table 6.10 and figure 6.6 show the breakdown of demand over the ten-year LunA-10 time window, assuming the hardware takes two years to arrive on the Moon. It includes the number of foundries at the pilot-scale to meet the manufacturing demand, showing the time dependent scaling of these axes. Further description of the time periods (Foundational Age, Industrial Age, etc.) are discussed in chapter 14.

Table 6.10. Product mass scaling study results summary

Product	*Year*							
	3	*4*	*5*	*6*	*7*	*8*	*9*	*10*
	Product Mass, t – Aluminum Rail							
Rail Aluminum6063	2.64	54.39	4.4	121.3	598.0	1591	1591	1591
Radiator Iron	0.54	0.01	3.22	81.2	556.5	844.5	1289	1289
Add Manufacturing Aluminum4043	0.1	1	5	10	50	100	500	1000
Power Transmission Aluminum1100	0.09	1.92	1.92	4.26	21.28	56.76	56.76	56.76
Tower Aluminum6063	4.15	<.01	5.67	40.27	79.3	25.19	36.75	<.01
Rover Parts, High--Carbon Steel	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Product	*Product Mass, t – Steel Rail*							
Rail Steel	6.96	143.6	11.61	320.2	1579	4200	4200	4200
Radiator Iron	0	0	0.02	0.56	3.11	21.88	69.23	69.23
Add Manufacturing Aluminum4043	0.1	1	5	10	50	100	500	1000
Power Transmission Aluminum1100	0.09	1.92	1.92	4.26	21.28	56.76	56.76	56.76
Tower Aluminum6063	0.21	0.05	0.53	3.18	5.33	15.4	19.25	0
Rover Parts, High Carbon Steel	0.09	0.01	0.2	0.97	2.59	2.59	2.59	2.59

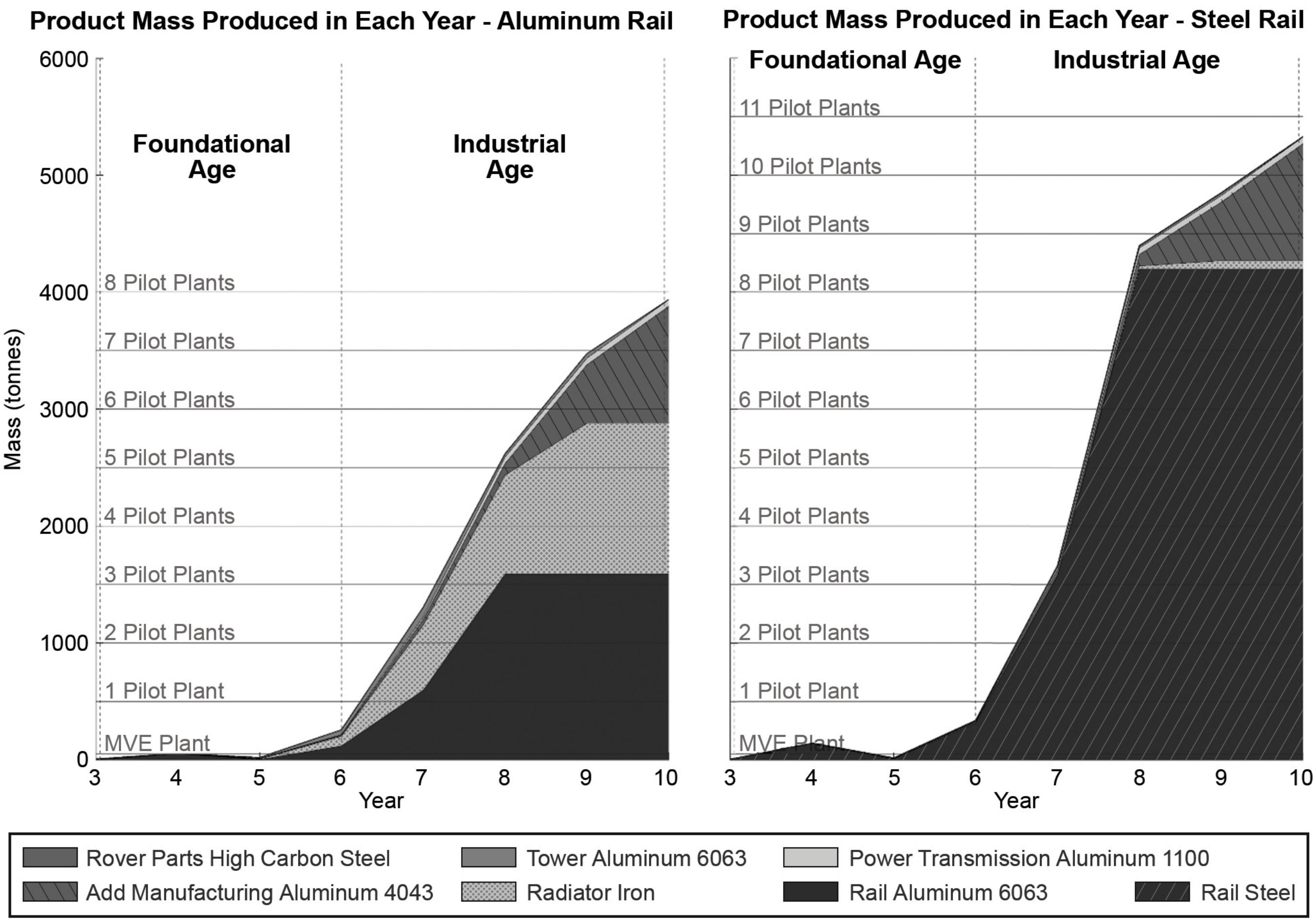

Figure 6.6. Foundry product production by mass versus year; (left) aluminum rail and (right) steel rail.

This demand in table 6.10 was processed through the energy models to calculate the energy required to meet the demand. Results are presented in table 6.11 and figure 6.7.

Table 6.11. ISRU energy demand over time

Energy Need	*Year*							
	3	*4*	*5*	*6*	*7*	*8*	*9*	*10*
	Power Demand (MW) – Aluminum Rail							
Distillation energy	0.03	0.43	0.13	0.75	3.2	7.57	9.35	11.35
Smelting energy	0.06	0.87	0.28	1.55	6.66	15.65	19.39	23.46
Mining & transport energy	0	0.03	0.01	0.12	1.12	1.7	2.6	2.6
Energy Need	*Power Demand (MW) – Steel Rail*							
Distillation energy	0	0.01	0.03	0.07	0.33	0.73	2.47	4.55
Smelting energy	0.01	0.06	0.07	0.24	1.1	2.65	6.22	10.45
Mining & transport energy	0.01	0.29	0.02	0.64	3.18	8.47	8.57	8.57

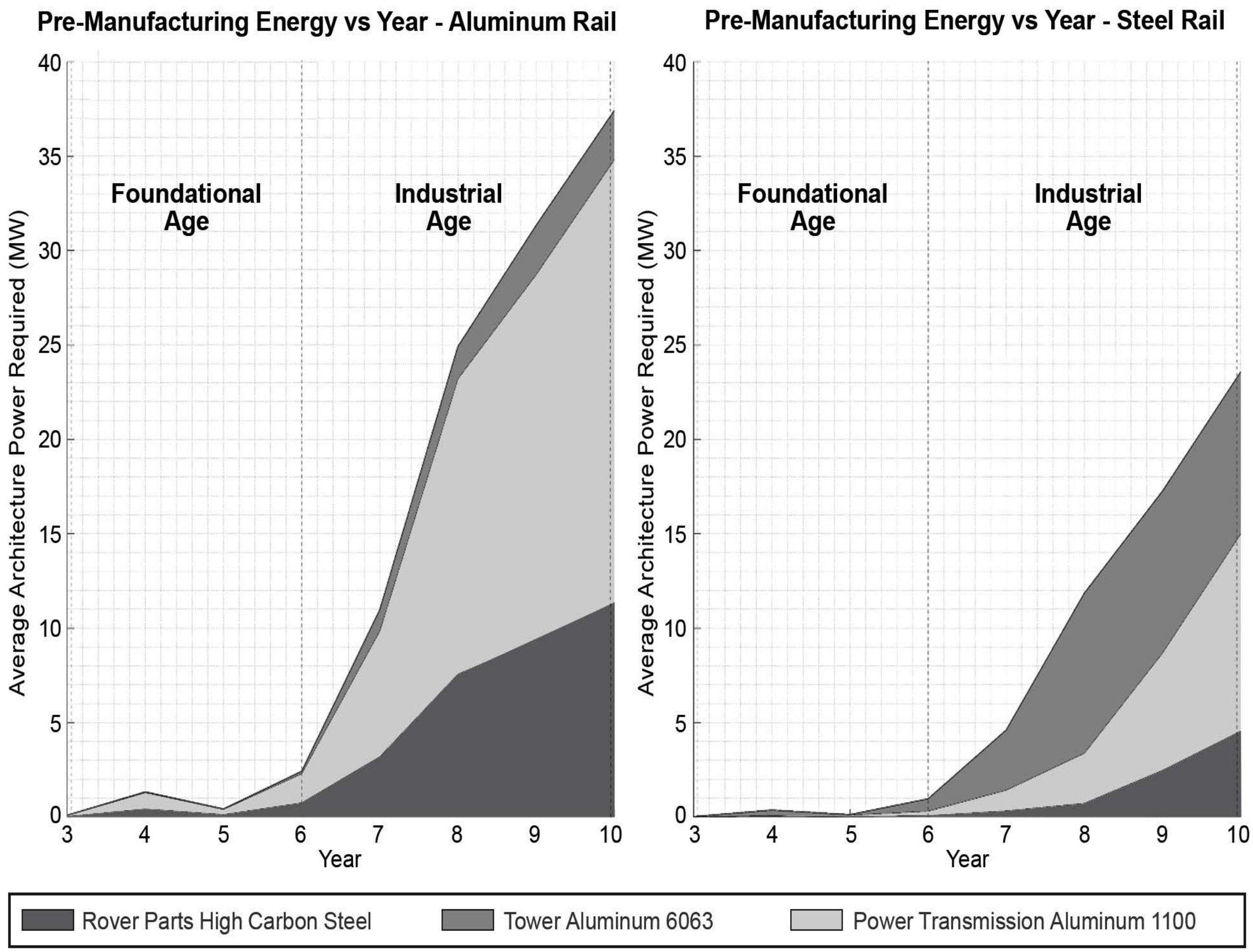

Figure 6.7. Energy consumption for ISRU metal refinement by year. (Left) aluminum rail and (right) steel rail.

Finally, this demand is factored into the model to generate the total processed mass required to manufacture the desired products. Results are shown in table 6.12 and figure 6.8. Leftover mass generated by the processing of ISRU materials but not used in products represents "wasted" material over the multi-year period and additionally shows the manufactured products from the chart above for scale. This output can aid in adjusting material selection for products and gauge potential areas for metal applications in the future.

Table 6.12. Cumulative material production for aluminum rail (top) and steel rail (bottom)

Material	*Year*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
	Material Mass, t – Aluminum Rail							
Manufactured products: Total	7.51	64.83	77.52	277.2	1562	3923	6091	7410
Unmanufactured CaO	9.03	83.17	105.1	332.8	1302	3597	6431	9872
Unmanufactured Si	6.25	153.8	200.1	357.7	1028	2616	4578	6961
Unmanufactured Mg	4.61	42.44	53.7	169.9	664.8	1837	3287	5051
Unmanufactured SiO2	0.3	0.42	0.42	33.66	334.5	792.1	1490	2188
Unmanufactured Ti	0.77	7.06	8.93	28.27	110.6	305.5	546.6	839.7
Unmanufactured Fe	0	17.61	20.02	0	0	0	0	0
Generated O2	17	270.1	348.2	790.5	2758	7283	12939	19729

Material	*Year*							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
	Material Mass, t – Steel Rail							
Manufactured Products: Total	7.45	154.0	165.8	358.4	2000	6058	9245	10177
Unmanufactured SiO2	3.79	81.05	87.43	260.6	1113	3386	5686	7987
Unmanufactured CaO	0.51	4.26	13.87	36.37	135.2	356.7	1107	2487
Unmanufactured Si	0.35	2.85	9.41	24.79	92.19	242.7	760.2	1715
Unmanufactured Mg	0.26	2.2	7.16	18.77	69.8	184.1	571.7	1285
Unmanufactured Ti	0.04	0.36	1.19	3.11	11.57	30.52	94.75	212.9
Generated O2	2.97	51.11	72.43	206.6	844.9	2468	5092	8891

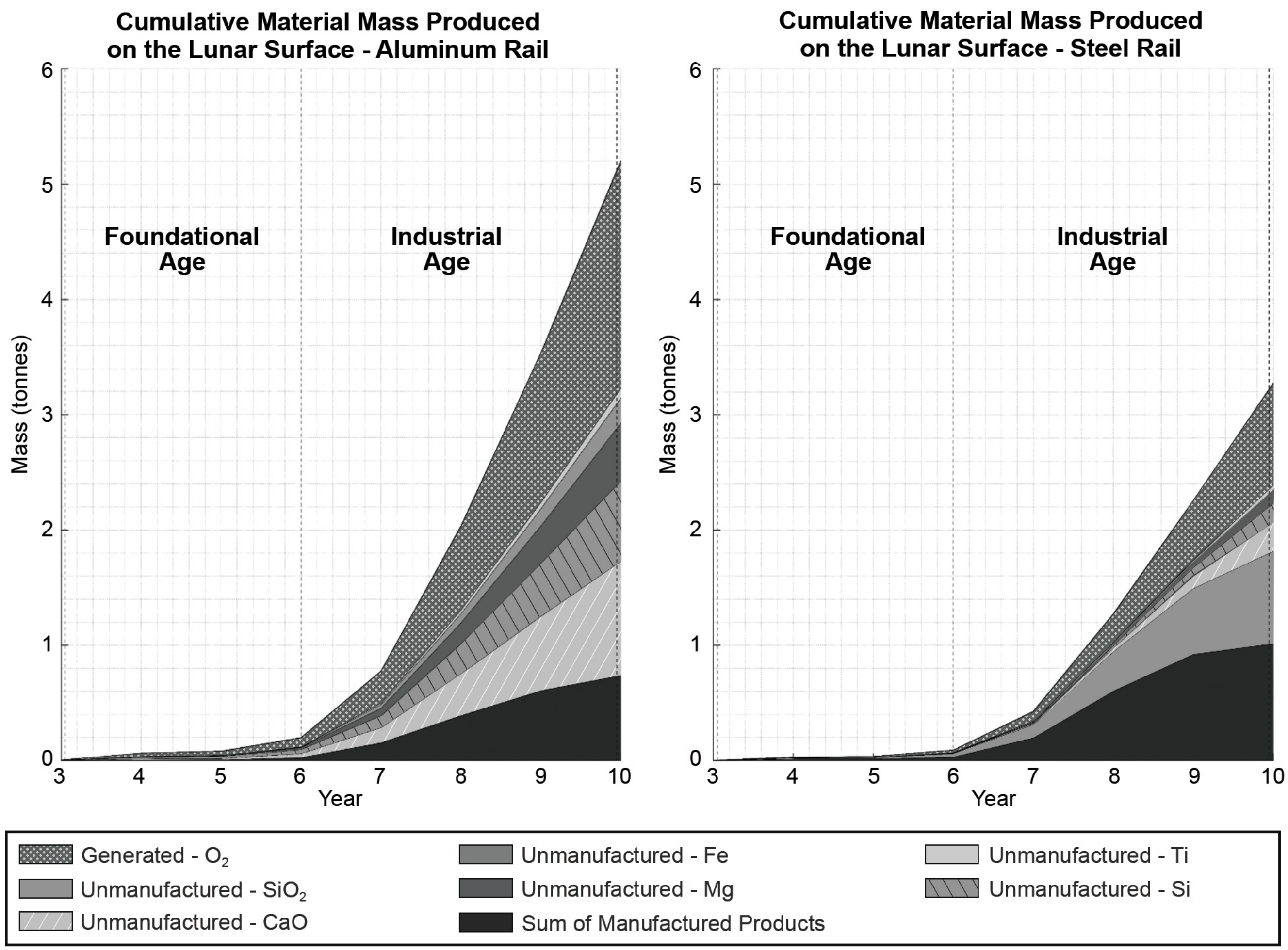

Figure 6.8. Cumulative material production. (Left) Aluminum rail; (Right) steel rail

The results show that switching from aluminum to iron as the base metal for lunar rail could lead to significantly lower overall energy requirements and a reduction in unused material. However, the higher mass of iron would require additional foundry capacity to meet demand, and the development of additional processing systems (e.g., rolling mill).

6.7 Recycling Case Study: Re-ISRU

This section investigates how defunct man-made objects on the Moon (e.g., landers and obsolete infrastructure systems) could be deconstructed, recycled, and used as source of materials for in situ metal manufacturing. Discussion with other LunA-10 companies yielded two potential concepts of operation for processing of scrap materials. In both cases, the recovered scrap material is transferred by rover to a collection yard near the foundry, where it is further processed into smaller sections that can be fed into the foundry for re-melting and recovery of the metal components. Materials that cannot be processed are stored in the scrapyard for possible later use as processing capabilities are improved.

Metal recycling offers several key benefits to the lunar economy. Objects such as landers will yield high-grade aerospace alloys and materials that cannot be made using lunar resources alone. Examples of products for lunar industrial applications that require high-performance metals are shown in table 6.13. Recycling is significantly more efficient than metal extraction processes: for aluminum, recycling consumes 1 percent to 5 percent of the energy required for ISRU aluminum extraction. Finally, recycling is a much simpler process than ISRU extraction and may therefore be the first process that can reliably provide in situ metals at an early epoch of the lunar economy.

Table 6.13. Selection of materials available through lunar recycling

Material	*Source*	*Applicability*
Series 300 stainless steel	SpaceX lander	Does not become brittle at low temperatures, useful for products where high strength and flexibility are required, such as springs and wire rope.
Inconel	Engines & components	High nickel content, can be used for high-temperature applications or to make nickel-iron alloys with good low temperature performance
High-grade aluminum alloys	Lander structures	Useful for high-performance structural applications
Carbon	Composite structures	Useful to make steel from ISRU iron, can be used to resupply processes that require carbon, such as the carbothermal process
Copper	Electronics	Useful as an alloying element in several high-performance aluminum alloys

Despite this strong promise, significant challenges must be overcome for lunar recycling and Re-ISRU to be a viable market. Concerns such as protection of disassembled intellectual property and legal ambiguity around transferring ownership and liability on the Moon need to be conclusively addressed. Further, spacecraft are designed on decades of flight experience and engineering practice that has never considered recyclability. Such objects will likely present significant technical challenges to deconstruct in a manner consistent with repurposing their resources. These concerns must be addressed before the market becomes viable.

Deconstructing complex man-made objects requires versatile processing systems to cut and separate materials. In the early days of the market, recovered materials will be limited to those that are relatively "easy" to separate. The overall yield will therefore be low. In the future, spacecraft designers can be encouraged to design for easier recycling by offering economic incentives, such as higher prices offered for scrap that is easier to process. Improvements in processing techniques and eventual adoption of design-for-recycling principles will, over time, improve recycling yields.

While the Re-ISRU process has the potential to expose intellectual properties during the process of deconstruction, select terrestrial companies are entrusted with the destruction of sensitive materials. As the Moon becomes more crowded, this destruction of sensitive material can itself be sold as a service to prevent discovery and industrial espionage by third parties.

Transfer of ownership and liability will require discussion at the level of governing bodies to establish precedent and provide clarity for commercial companies. This is a critical need to enable this new technoeconomic vector for the lunar economy; the international community must begin to lay the groundwork to clarify these questions today. Two methods by which to do so, a future Lunar Development Cooperative (chapter 18) and an international interoperability standards community (chapter 22), are discussed in this *Field Guide*.

6.8 Summary of Key Findings

A comprehensive system design and energy requirement analysis was performed, with energy consumption rates and subsystem energy needs calculated. Broad challenges in energy consumption were identified. An assessment of key energy cost drivers pinpointed specific capability improvements in prospecting, mining, and beneficiation that could significantly reduce overall energy consumption. The framework and system overview outlined critical components and processes within the ecosystem, including the foundry unit. The design considers the harsh conditions of the lunar environment and highlights the need for close and early integration with other commercial services.

The economic model marks an initial insight into the cost effectiveness of lunar metal processing relative to Earth-sourced materials. Although the model highlighted high initial investment costs, it also identified promising avenues for cost recovery and profit generation through strategic resource utilization and market positioning.

Recycling case studies revealed significant potential for reducing waste and repurposing materials while highlighting some critical challenges. Development of a recycled metals market will require coordination between the lunar community, governing bodies, standards organizations, and commercial entities but has high potential benefit to the global lunar economy.

Carbon has been identified as a key element with high value due to its scarcity in situ and its importance in steel production and processing. Most landers will yield composite components, which can be recycled as a source of carbon.

Several promising products were identified that can be created with a small number of simple fabrication systems, which can then be applied to infrastructure and development of the lunar economy. These specific products underscore the practical applications and market potential of a lunar metal ecosystem.

An overarching insight relevant across the LunA-10 architecture is that **the development of a viable lunar ecosystem will require a shift to a different set of design and operational paradigms: designing for recyclability, repairability, and maintainability. This will achieve long-lived, repairable systems that are robotically maintained with high system availability**.

The energy estimates developed in this chapter provide an important understanding of the relative energy requirements for ISRU metal production. This sets a baseline for the operational costs associated with the foundry, which directly influences the economic model's projections on profitability and cost recovery timelines. Understanding the energy consumption helps identify efficiency improvements and alternative energy sources, improving the economic outlook of the proposed metal value chain. They provide insight into the significant power requirements of the foundry in particular and ISRU production in general. This work underlines the importance of innovative solutions for energy efficiency and alternative funding models to enable the creation of a lunar economy.

The findings from the recycling case study demonstrate the potential for waste reduction and resource optimization. Recycling contributes not only to economic viability but also to reducing the ecological footprint of lunar operations, placing sustainability front and center.

In the near term, metal is economically manufacturable at scale on the Moon, providing a significantly cheaper alternative to launching from Earth. Assuming launch costs trend down with time, operations can scale by sending multiple pilot plants as projected demand grows, in place of a singular, larger plant with a high production capacity. This will minimize costs of sending excess capacity while transportation costs are high and improve time-cost averaged amortization of costs, keeping in situ production of goods competitive to imported launched goods.

Using assumptions based on the current state of the art for power generation on the Moon and material input cost, economic modeling concludes that the foundry system is commercially viable relative to imported materials down to $10,000/kg transportation cost with near-term technology and minimal optimization. With further reduction of energy and resource extraction costs, which are expected as the lunar economy matures, the foundry system can be viable relative to transportation costs below $100/kg. Given production costs this theoretically low, additional opportunities are opened for export of material from the lunar surface to the rest of space; these would be able to economically compete with Earth-sourced mass.

In conclusion, the research presented in this chapter has laid a strong foundation to assess the feasibility of metal processing on the Moon. The developed metal processing framework serves as a cornerstone for future developments. As further technological innovations and collaborations move forward, a focus on improving energy efficiency, enhancing system integration, and developing a robust recycling ecosystem will be paramount.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Richter, Schroeder, Mould, Pawelski, and Calnan are from CisLunar Industries.
2. Javid & Company Inc.
3. Omnetix LLC.
4. ReliAvail Technologies Inc. and Queen's University.
5. Authors Petruska and Corwin are from Colorado School of Mines.
6. Pioneer Astronautics (purchased by Voyager Space).
7. Defense Advanced Research Projects Agency (DARPA).
8. Mould et al., "Space Foundry: Recycling Space Debris"; Schroeder et al., "Space Foundry Lab Module on the ISS"; and Schroeder et al., "Orbital, Lunar and Planetary Infrastructure."
9. Schroeder et al., "Space Debris Recycling by Electromagnetic Melting," 309–34, in *Handbook of Space Resources*.
10. For more information about value chains, see chapter 15.
11. Down-mass refers to the mass of material returned to the Earth.
12. See chapter 9 as an example.
13. Numbers based on expert conversations with members of the LunA-10 consortium.
14. Beneficiation methods include electrostatic and particle sorting as well as magnetic separation, which is particularly useful for ferromagnetic oxides like iron oxide.
15. Schreiner et al., "Parametric Sizing Model."
16. Schreiner et al., "Thermophysical Property Models for Lunar Regolith"; and Schreiner et al., "Parametric Sizing Model."
17. BCS, "U.S. Energy Requirements for Aluminum Production."
18. Nayak, "Six Hypotheses to Accelerate a Lunar Economy," arXiv, March 2024, https://doi.org/10.48550/arXiv.2403.05959. Terrestrial industrial silicon, GaN, and SiC crystal growth use the Czochralski method, which relies on gravity. Wafer Scale Integration in lunar gravity allows for growth of super large chips with minimal to zero defects per wafer. Terrestrial silicon boules have not been produced larger than 450mm; many times this diameter may be grown on the lunar surface. The Czochralski method is well established and could be applied to crystal growth on the lunar surface. Building an industrial scale fabricator on the lunar surface has benefits over an orbital fabricator. Providing the power levels required for industrial boule production may be simpler on the lunar surface. Lunar regolith contains high concentrations of silicon and is a significant byproduct of O2 production. Producing highly refined silicon with lunar regolith on the lunar surface may have benefits over terrestrial production especially when combined with crystal growth benefits (Nayak, "Six Hypotheses").
19. BCS, "US Energy Requirements for Aluminum Production."
20. Kalpakjian and Schmid, *Manufacturing Engineering and Technology*, chap. 15.
21. Kalpakjian and Schmid, *Manufacturing Processes for Engineering Materials*.
22. CLPS: Commercial Lunar Payload Services, a NASA-funded program for commercial lunar landers.
23. Colvin et al., "Demand Drivers of the Lunar and Cislunar Economy."
24. RASSOR: Regolith Advanced Surface Systems Operations Robot, a NASA-funded, teleoperated, mobile robotic platform with reduced-gravity regolith excavation capability.

7

Communications, Position, Navigation, and Timing

Edited by Michael Nayak

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7.1 Introduction and Framing

As the cadence of lunar missions increases, surface and orbital users will need reliable communications and positioning, navigation, and timing (PNT)—collectively referred to as Comms/PNT—as a foundational service for lunar infrastructure. PNT will be crucial for the precise operation of vehicles and equipment including rover navigation, astronaut positioning, habitat construction, scientific exploration, and backbone logistics of lunar construction projects. PNT services enhance the autonomy of operations, reduce the risk of collisions in space, and improve accuracy of all lunar activities by providing precise timestamps and location data. It is also expected that Comms/PNT services will play a role in risk reduction and data telemetry for commercial space insurance purposes.

A system of shared and dedicated Comms/PNT terminals of minimal mass, particularly if offered as a scalable product, can simplify user equipment and reduce overall mission complexity. As a commercial service, this common infrastructure element can lower the barrier to entry and contribute to the growth of the lunar ecosystem.

This chapter will explore three concepts for commercial lunar Comms/PNT:

1. A scalable multiservice Modular User Surface Terminal (MUST), which includes the following commercial services: direct-to-earth (DTE) communications, surface area networking (SAN); PNT; space traffic management (STM); survive the night (STN) thermal; and, eventually, onboard data storage and processing (ODSP).

2. A scalable optical communications node, co-located with an optical wavelength power beaming service such as the Lunar Infrastructure Optical Node (LION) discussed in section 4.2.3.

3. An orbital node for Comms/PNT, which can be combined with a radio frequency survey service.

One common thread, pioneered by LunA-10, is that each of these solutions is fused and co-optimized with as many other infrastructure services as possible. Each is scalable to various standard payload sizes that, in the future, support large-scale ubiquitous infrastructure. These system-level solutions allow the creation of a quantitatively defendable analytical framework for future lunar infrastructure (presented in chapter 14) that leverages technology overlap between commercial services to the maximum extent possible, the necessity of which was a key finding of the LunA-10 program.

7.2 NASA's Vision for Comms/PNT: LunaNet

LunaNet is NASA's interoperability specification framework,[13] which will identify the Lunar Reference System (LRS) and the Lunar Time System Standard (LTC). LunaNet is being developed primarily to support NASA's Artemis missions, particularly in the south pole region.

7.3 Scalable Unit No. 1: Modular User Surface Terminal (MUST)

Through the LunA-10 program, Crescent Space evaluated its commercial Modular User Surface Terminal to explore more size, weight, and power (SWaP)–efficient solutions. This resulted in the design of four different architecture options sufficient to support the communications and PNT needs of the lunar economy through 2035. These options are summarized in figure 7.1. These terminals are agnostic to any hosting platform, can be integrated into other services, and connect to any LunaNet compliant lunar orbiting relay.

7.3.1 Scalable Configurations

MUST-MVP (minimum viable product) is the smallest modular unit, offering an Earth communications system (ECS) and PNT services. This unit would primarily allow users on the lunar surface to communicate to an orbiting relay or DTE and determine its position and time. The primary use case is service-dispersed missions operating independently, without another infrastructure element in line of sight, while freeing the mission from bringing its own hardware. MUST-MVP is <0.7kg and requires <20W for operation.

MUST-SAN is the next size up, offering SAN and PNT services. This unit would primarily support an independent SAN user (e.g., a small rover) for lunar surface communications. MUST-SAN is <0.75kg and requires <40W for operation.

The nominal MUST unit is a combination of MUST-MVP and MUST-SAN configurations, with added STM and STN thermal and electric capabilities. The base MUST unit is <1.5kg and requires <60W for operation.

MUST-Heavy is the largest configuration, which provides all services (ECS, SAN, PNT, STM, and STN) in its base version, with added bandwidth capability in Ka-band. MUST-Heavy can support a human landing system and would enable a multi-node SAN infrastructure and mesh network on the lunar surface. MUST-Heavy is <20kg and requires <125W for operation.

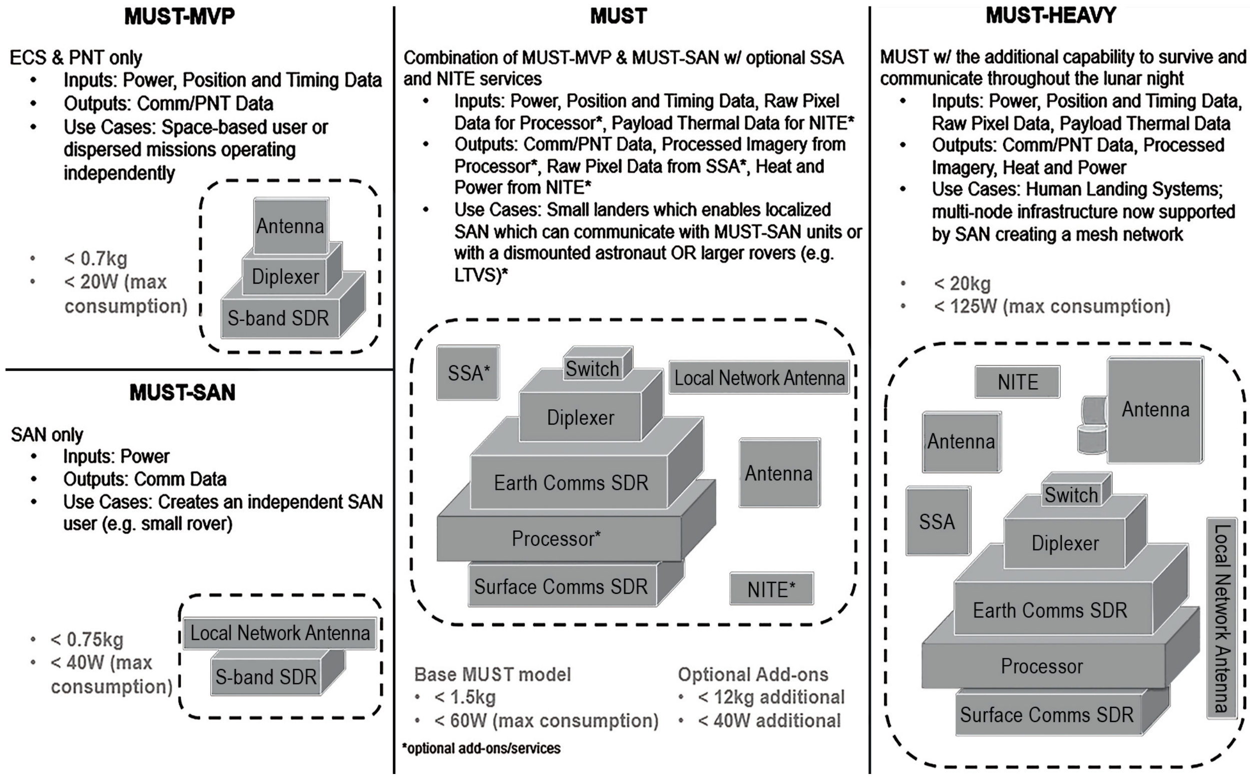

Figure 7.1. Summary of various scalable Comms/PNT commercial units. (Credit: Crescent Space)

7.3.2 Commercial Services: Earth Communications System

The MUST ECS communications subsystems leverage development of the commercial Parsec S- and Ka-band payload's software defined radios (SDR), software defined processor, and RF components. The communications service is interoperable with LunaNet and intended for use with lunar surface and orbiting users to provide streamlined connectivity to communications relays and other MUST units using standardized protocols.

LunaNet interoperability standards allow for overlap between communications from the lunar surface to relay satellites and Earth. Adjacent frequency bands and compatible waveforms, with the use of SDRs, allow an ECS system to flexibly support communications to either destination. S-band, X-band, and Ka-band are currently supported and are the specified frequency bands for lunar relay spacecraft.

Initial MUST customers are lunar payloads or small robotic landers/rovers. ECS and SAN functionality can offer flexibility to landers and rovers that are host to other payloads. Communications during the cruise from Earth to the Moon can be accomplished on the same MUST ECS service that will provide backhaul once on the Moon, eliminating redundant communications hardware.

Human exploration and permanent lunar infrastructure will exponentially increase the number of data streams routing back to Earth. MUST is designed with this future in mind and multiplexes local communications needs into a smaller number of communications channels back to Earth.

Initial robotic landers and small scientific payloads can operate with tens to hundreds of kilobits per second of data to Earth. This would use MUST-MVP with a small omnidirectional antenna. Added directive antennas will stay ahead of the future need to close the backhaul link at megabits (Mbps) per second.

Body-fixed medium gain antennas can also be added. These will allow for ten times the data rate of the omni antennas. As data rates continue to rise, steered antennas will become necessary, and gimbaled or electronically steered high gain antennas can achieve rates up to 100 Mbps at Ka-band.

7.3.3 Commercial Services: Surface Area Network

A surface area network is formed by a network terminal (radio, processor, antenna) within the MUST unit. The SAN system uses a millimeter-wave SDR and antenna to create a local communications network for routing, prioritization, processing, aggregation, and transfer of data between users. It utilizes standardized, interoperable protocols and interfaces. The signal scheme will be chosen to minimize lunar adaptations to existing hardware while remaining compliant with commercial-focused lunar interoperability standards (chapter 22).

When coupled with the STM sensor, this SAN can enable highly accurate localization and navigation. Accuracy increases and time-to-fix decreases as additional network terminals arrive on the lunar surface.

MUST can provide support for robotic missions requiring deployed or mobile payloads that cannot stay harnessed to the delivery lander. An S-band point-to-point network using frequency or time multiplexing, or a limited Wi-Fi network, may allow the fastest schedule for providing a limited area network. Initial implementations of the SAN service will focus on aggregating and distributing communications at the central MUST unit, to support a simple data routing system for distributed users.

As the lunar ecosystem develops, larger coverage from multiple towers will become necessary to handle more complex data routing without utilizing Earth as the "central router." This infrastructure-level SAN will leverage third generation partnership project (3GPP) standards to provide users with networks extending kilometers from the central MUST unit. Mounting the MUST-SAN service on a tall tower (see chapter 10) enables Mbps coverage across a 10–20 km area of operation.

As 3GPP MUST-SAN service increases, multiple tower-mounted MUST units can communicate with each other, extending the size of the SAN and optimizing the efficiency of data routing in the local area. 3GPP standards also provide increased accuracy of positional knowledge with additional datasets of distance and angle from MUST to the users.

7.3.4 Commercial Services: Position, Navigation, and Timing

As with the ECS and SAN services, the PNT service will grow to match the expected user needs. MUST will receive and transparently turn around phase-coherent Doppler and pseudo-noise ranging signals within the ECS subsystem. The Doppler and ranging radiometric signals are modulated as part or on top of the communications signal. The returned radiometrics are measured at the source (either terrestrial ground stations or lunar relay orbiters); that data is used to determine the position of MUST.

The current instantiation of this PNT solution requires terrestrial processing. So, MUST position will be determined in the operations center of the user, which can then be uplinked to the MUST host if desired. As the lunar communications ecosystem develops, radiometric and additional datasets will be available to integrate into a more accurate, real-time PNT solution.

NASA's planned Augmented Forward Signal (AFS) service aims to provide a GNSS (Global Navigation Satellite System)-like transmitted signal from a constellation of lunar orbiting satellites. MUST can be modified to receive and process these signals. Initially, PNT solutions will still require terrestrial radiometrics. Eventually MUST will be able to provide significantly shorter time-to-first-fix PNT solutions based on three or more AFS transmitting orbiters.

MUST will continue to determine its own location based on terrestrial/orbiter radiometric signals and locally generated STM imagery. As 3GPP SAN services are rolled out, relative range and angle of other surface elements can provide highly accurate PNT solutions.

7.3.5 Commercial Services: Space Traffic Management

The lunar domain is of tremendous commercial and strategic value, and as commercial entities expand their activities, increasingly advanced sensors and systems must be deployed to observe, understand, and detect objects, spacecraft, and debris. The Lunar-OWL system from Scout Space, integrated within the baseline MUST unit, produces high-fidelity measurements and advanced exploitation capabilities, toward an exquisite new set of lunar domain data. This visible-wavelength sensor can create an affordable, rapidly deployable, high-fidelity sensor for space traffic management that can be deployed in any lunar environment.

Lunar-OWL is a high-performance, SWaP-efficient optical system designed for long-range imaging and object tracking, facilitating STM data-as-a-service through taskable and opportunistic data collection. This ensures comprehensive coverage and real-time object tracking in the lunar environment. Designs for such sensors have a range of SWaP attributes, offering varying weights (15-35 kg) and power (55–75 W), capable of long-range lunar STM for satellite visible magnitudes (Mv) of <16–18 Mv.

One of the major obstacles for STM sensors is the highly adhesive lunar dust, which negatively affects optical systems and sealed gimbal mechanisms. Both passive and active dust mitigation strategies are required, including mechanical housings coated with dust-repelling materials and the use of an electrodynamic dust shield for optical surfaces. The gimbal mechanisms may require multiple seals and dust-tolerant umbilicals. Additionally, the STM sensor may require heating elements to keep critical components above night survival temperatures.

7.3.6 Commercial Services: Survive the Night (STN)

One example of a low-mass, high-energy density lunar night survival heater, which also provides some electrical energy, is the Nighttime Integrated Thermal and Electricity (NITE) from Astrobotic. During LunA-10, NITE was integrated into MUST and MUST-Heavy designs. It replaces batteries with a more energy dense solution for short duration (three to twelve lunar nights) survival and also provides adjustable heat output, which may be advantageous over a fixed-output radioisotope solution.

Such STN systems provide heat via oxidation of a solid metal fuel by a liquid oxidizer. Initial testing achieved seven to nine times the energy density (Wh/kg) of state-of-the-art lithium-ion batteries, with an energy grade split of 80 percent thermal, 20 percent electrical. While these tests were performed in the 10 W output range, future STN systems may be scaled to support higher power levels.

Because such STN systems rely on fuel consumption/combustion to produce power, increasing the system run-time scales favorably compared to batteries. The desired minimum run time is three lunar nights. At three nights, the rate of increase in marginal efficiency gained by adding more fuel hits an inflection point. Efficiency approaches the limit of the chemical energy content of the fuel. After twelve lunar nights, rechargeable battery systems become advantageous again, as the added fuel mass matches the added mass of a solar recharging system for a given battery size.

Most of the heat is produced in a small location. A thermal management system could be used to direct the heat as needed on a lunar surface payload. However, in evaluating the added mass of such a system, the best implementation appears to be to install STN systems inside the insulation of systems to be heated. Much like a terrestrial portable room heater, STN systems can then focus heat on the most critical subcomponents, but the ambient heat of the rest of the system can be radiated to heat the insulative enclosure. Using fuel and oxidizer also makes STN systems a possible lunar customer for ISRU metals (section 6.1) and lunar water ice-derived liquids, providing a key link to close a previously discussed lunar surface commercial economic cycle.

Since both the metal fuel and the oxidizer are storable, heat and power can be provided at any time without the challenges of excess heat rejection posed by nuclear generation or the excessive mass incurred by battery systems. The "exhaust" products of heat and power generation are metal oxides and hydroxides. The metal oxides can be sold back to regolith-based oxygen extractors as a high-grade feed stock. Metal hydroxides may be sold as a flux for MRE, as well as a geopolymerization catalyst for regolith-based construction using binder agents.

7.3.7 Scaling and Commercialization

Each of MUST's services are intended to scale as the market demand and infrastructure needs grow. MUST will initially employ a low-rate S-band SDR and antenna. Small S-band patch array antennas would be suitable for missions with low data volume SAN needs.

As seen in figure 7.1, MUST can be scaled down by removing and simplifying elements to support specific user mission needs. These smaller, simpler terminals include the ability to connect with local surface networks for rapid and responsive deployments and may be distributed across the lunar surface to cover a larger effective area than a single MUST unit.

As backhaul needs increase, the antenna can be scaled up to higher gain S-band antennas. Second-generation units can transition to smaller antenna form factors for Ka-band or dual-band radios. Data rates up to 100 Mbps transmit and 40 Mbps receive to orbital relays can be achieved using electronically steerable Ka-band arrays or deployable Ka-band reflector antennas with diameters of 0.7 m. The first- and second-generation units will use the same physical and data interfaces with the SDR hardware.

The SAN will use wide-beam antennas to maximize the antenna gain toward the horizon in all directions. The SAN SDR can adjust RF output power levels to increase range or minimize power consumption for unique mission scenarios. For coverage from multiple towers (chapter 10), the SAN architecture will leverage 3GPP standards to provide a Comms/PNT network extending kilometers from the central unit.

The MUST commercialization strategy involves three main pillars:

1. Pre-mission. Core unit hardware sales, to include mobile user communications terminals.
2. Mission execution. Services: communications, navigation, situational awareness, data storage, and data processing.
3. Post-mission. Data sales: imagery data and network usage statistics.

Hardware sales target any lunar mission, regardless of scale and type. Larger infrastructure elements can use full MUST units to act as a lunar cell tower on the surface. Smaller, more focused users can use MUST-MVP units to drastically simplify their communications subsystems and improve data throughput and mission reliability. These hardware sales can be coupled with services sales in subscription or user-tailored pricing models to incentivize more data throughput over longer periods of time.

In the Foundation Age timeframe (see chapter 14), primary hardware sales will begin with MUST-MVP and MUST-SAN units for landers, rovers, and limited crewed systems. As the frequency of missions and volume of data required increase, hardware sales are expected to transition to primarily MUST-HEAVY units serving early infrastructure elements. Once large-scale infrastructure using concentrated and interdependent nodes is established, hardware sales will shift to MUST units with 3GPP SAN capabilities.

Services will begin with usage-based pricing schemes that address the quantity of system resources used. Customers can choose packages that include specific data throughput and data rates for communication, access to PNT signals, processing for position and velocity measurements, memory, and compute resources. Once sufficient continuous demand for services over extended durations exists, MUST will be offered on a subscription basis to encourage high utilization and increased mission duration and scope. This is similar to terrestrial cell network providers.

Data sales include both raw data and compiled data products; this category targets both lunar and terrestrial customers for mission planning, execution, and postprocessing. Examples include imagery and remote sensing data collected while not specifically tasked, terrain maps, domain awareness information, and network usage statistics. MUST is a relatively low-cost, low-SWaP concept that is easily manufactured and integrated into a variety of missions. The simple and modular design results in a low amount of nonrecurring engineering to cover the optimization and production costs of the terminals. Economies of scale in production cause unit costs to decline as lunar traffic increases.

This commercialization approach allows for both upstream and downstream revenue and de-risks the overall business case by offering different revenue streams at different phases of the market. The early revenue will come from MUST hardware sales (up to one year pre-mission). Service sales happen during the mission, and downstream revenue will come mostly from data sales post-mission. Data sales may be purchased by users on Earth who wish to use such data, further de-risking the overall business case.

7.4 Scalable Unit No. 2: Lunar Infrastructure Optical Node (LION)

Optical communications offer high-bandwidth, directional, and secure communication, making it ideally suited for use in the lunar environment. High-power laser power beaming across the lunar surface was discussed in section 4.2.1. This same unit can also provide optical backbone transport, including secure optical communications from surface to Earth and lunar orbiter (200 Mbps to 2 gigabits per second [Gbps][14]); secure optical communications across the lunar surface (Gbps); and precision time transfer from Earth and lunar distribution (accuracy of 1 nanosecond). The proposed services support sustained commercial lunar activities; science community requirements for high-data-rate sensors; future planetary, astrophysics, and heliophysics missions; synthetic aperture radar, light detection and ranging (LIDAR) and high-resolution imagery; and proposed scientific telescopes.[15]

To quantify this possibility, long-range optical communications link budgets, and corresponding maximum bandwidth, were modeled (section 7.4.2) and verified using commercial software and the Lunar Infrastructure Optical Node (chapter 4). Data backhaul with data rates of 1 Gbps are feasible. Optical communications across numerous bidirectional relays between the Earth and Moon show a path toward 100 percent availability from Earth to anywhere on the lunar surface.

7.4.1 System Description

For long-range comms, a laser communications terminal (LCT) has been merged with a power-beaming unit to create the overall LION system discussed in section 4.2.1. The optical assembly includes a 10 cm telescope on a gimbal assembly, with SWaP numbers of 30 liters, 15 kg, and 80 W. This LCT is designed to be interoperable with NASA optical ground station systems, is capable of on-off keying, and can host pulse position modulation waveforms. It would be appropriate for lunar surface, EM-L1, and orbiter missions; link budgets are discussed in section 7.4.2.

For short-range comms, similar terminals could support surface-to-surface 5–10 Gbps links, surface-to-low lunar orbit (LLO) at Gbps up to 100 km, and links to EM-L1 and direct to Earth at reduced rates (see table 7.1 for one example). The short-range LCT SWaP is ~5 kg, <20 W for surface-to-surface, and 30–40 W for surface-to-orbit communications.

7.4.2 Optical Comms Link Budgets

Multiple optical link modeling cases were considered; these include lunar surface to LLO, a highly elliptical near-rectilinear halo orbit such as one proposed to be occupied by NASA Gateway,[16] Earth-Moon Lagrange point 1 (EM-L1), direct to geosynchronous Earth orbit (GEO), low Earth orbit (LEO), and the Earth's surface. Orbit-to-orbit relay links were also included.

The link analysis results are shown in table 7.1. Hundreds of Mbps to Gbps data rates are available in most orbits, depending upon space telescope sizes, laser powers, and receiver sensitivities. The maximum range for each scenario is identified. The data link rate column is relative to ~10^{-2} bit error rate (BER). The user data rate is one-half of the value shown in the table to account for forward error correction, interleaving, and code rate "error-free" data assurance methods of 10^{-9} BER. Dynamic link propagation loss, carrier-to-noise, and energy per bit to noise power spectral density ratio were also determined over a period of days.

Table 7.1. Long-range (400,000 km) and short-range (100 km) optical communications link budgets

Orbit	*Max range (km)*	*Tx telescope diameter (cm)*	*Rx telescope diameter (cm)*	*Laser power (W)*	*Data line rate (Mbps)*	*Calculated link margin (dB)*
Lunar surface-Gateway Perilune	8,096	13	22	0.5	10,000	1.9
Lunar surface-Gateway Apolune	68,364	13	22	4	1,250	0.4
Lunar surface - L1	68,940	13	30	6	2,500	2.3
L1 - Lunar surface	68,940	30	13	20	10,000	2
L1 - Earth	356,510	30	150	20	4,000	5.3
L1 - GEO	394,124	30	16	20	300	1.1
L1 - LEO	359,167	30	13	20	100	3.2
Lunar surface - Earth	393,860	13	150	6	2,500	3.9
Lunar surface - LLO	857	13	13	0.25	10,000	13.8
Lunar surface - LEO	394,668	13	13	6	10	3.5

Key

dB: decibel

GEO: geosynchronous Earth orbit

L1: Earth-Moon Lagrange Point 1

LEO: low Earth orbit

LLO: low lunar orbit

Rx: receiver

Tx: transmitter

Key orbits are highlighted below.

- Lunar surface to Gateway. This is a highly elliptical orbit. Links range from 1 Gbps to 20 Mbps as a function of range. The apolune link rate can be improved with more laser power and a large telescope size on Gateway.
- Lunar surface to EM-L1. Robust bidirectional Gbps data rates can be realized with a 30 cm telescope at EM L1 and higher laser power. These data rates imply that EM-L1 can be a major relay node for intra-lunar traffic to the surface, LLO, and Gateway, as well as a supporting cislunar node for Earth traffic.[17]
- EM-L1 to Earth. The relay between L1 and Earth can provide up to 4 Gbps data rates with a 30 cm telescope and a 1.5 m ground station telescope. This makes an L1 relay very attractive for bidirectional traffic between Earth and the Moon.
- Lunar surface and EM-L1 to Earth. Gbps data rates for direct-to-Earth provide network path diversity and high data rates. This is partly enabled by the 1.5 m ground station telescope assumed and ultra-low noise cryocooled detectors available on Earth.

- Lunar surface to LLO. The link budget shows >>1 Gbps for bidirectional data given a 13 cm telescope size at ~1,000 km range. This result would apply to greater ranges with correspondingly larger telescope sizes.
- Lunar surface to lunar surface. For this link, the telescope diameter was reduced to 2.4 cm and the laser power lowered to 0.5 W. Nevertheless, data rates up to 10 Gbps can be achieved out to 100 km. SWaP estimates are 2.5 kg and <20 W of power for a smaller version of the LION terminal discussed below.

7.4.3 Scaling and Commercialization

Because all optical comms terminals (OCT) can operate independently, there is no inherent cost benefit with scaling to larger sizes. Cost benefits are instead achieved by production at scale. OCTs' inherent modularity enables scaling the capacity of any individual node to meet local requirements and support a high duty cycle, supporting a uniform service price as a function of local power input cost.

Table 7.2. Current best estimate price for OWPT and optical communications services. [Credit: Fibertek]

Service	*Industrial Age*			*Jet Age*		
	Mini	*LION*	*Multi*	*Mini*	*LION*	*Multi*
Number of nodes	8	8	8	16	16	16
Power ($/kWh)	$4,867	$3,488	$3,750	$1,717	$1,134	$1,271
Comms ($/Gb)	$1.47	$1.47	$1.47	$0.83	$0.83	$0.83

The current best estimate for optical communication to Earth or an orbiter is summarized in table 7.2, with a comparison to LION power beaming. As with power, this will need to be amortized over the duration of the power service (approximately 10 years) and is anticipated to be fully recoverable from a commercial perspective.

7.5 Scalable Unit No. 3: Combining Orbital RF Surveys with PNT

As part of LunA-10, Redwire Space studied a combined PNT and RF survey concept of operations. This combination leverages two antenna technologies that overlap in spectrum but fulfill very different missions: high-effective isotropic radiated power alternate PNT (aPNT) transmitting, using directional antennas combined with power amplifiers, and ultra-broadband antennas that cover multiple octaves of bandwidth for signal detection (SD) and scientific RF survey.[18] The active RF front end of the aPNT system can be combined with the bandwidth capabilities of the SD system and a custom receive front end for this mode of operation.

Figure 7.2 shows a block diagram for a half-duplex system that can handle PNT transmission and SD in a time-division scheme. The receive band may be separated into several sections of roughly one octave to overcome the bandwidth constraint of the quadrature branch line coupler. The PNT transmit function uses a 25 W (saturated) solid state power amplifier (SSPA) to provide aPNT, although this power level may change depending on the orbital altitude of the host spacecraft.

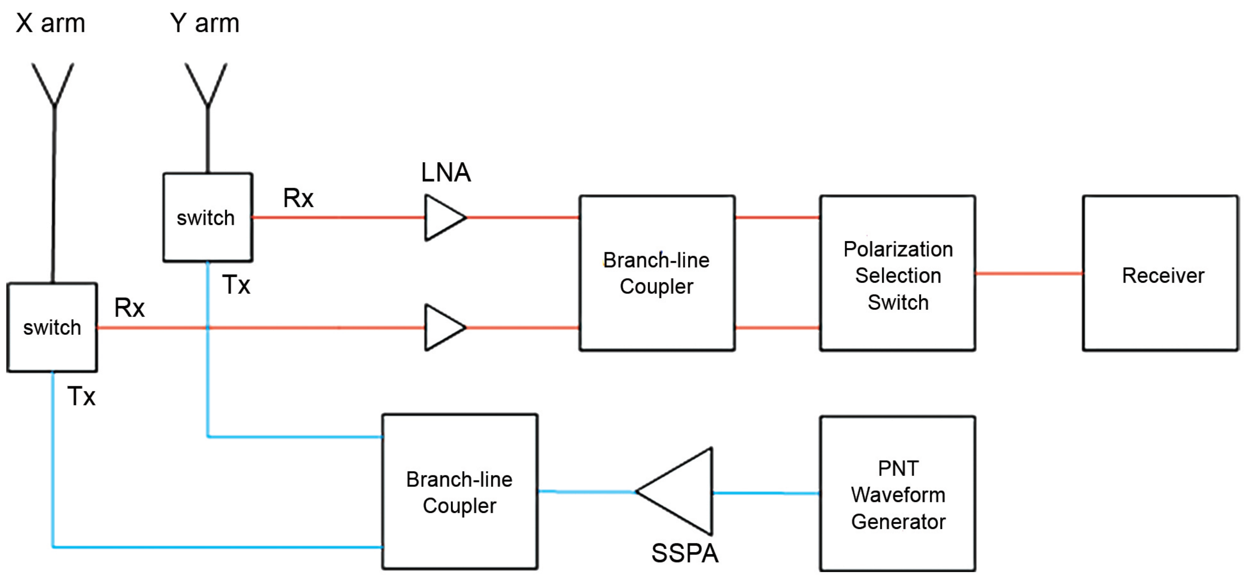

Figure 7.2. RF system architecture capable of switching between PNT transmit and SD receive functions. [Credit: Redwire Space]

The half-duplex system must turn off the PNT transmit function while operating in SD mode. This may limit the overall PNT system performance by increasing the number of satellites required to provide ubiquitous coverage across the lunar surface. An alternative architecture can provide full duplex or simultaneous PNT transmit and SD receive. This can be accomplished by replacing the two switches at the antennas with multiplexing filters that isolate the transmit and receive bands. In this scenario, the SD function would not be able to detect at the PNT frequencies. For PNT applications on the Moon, the resolution required varies depending on the application. For critical operations such as landing on rugged terrain or detailed scientific studies, resolutions in the sub-meter range might be necessary. For broader navigation and positioning tasks, 10-meter accuracy may be enough.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Bickus, Leeds, and Schray are from Crescent Space Services LLC.
2. SCOUT Space Inc.
3. Astrobotic Technology.
4. Lockheed Martin Space.
5. Authors Storm, Lapin, Kennedy, Whitener, Mack, and Petrillo are from Fibertek Inc.
6. Authors Turse and Saldana are from Redwire Space Solutions.
7. Authors Riley and Gorman are from Radar Applications Incorporated.
8. CACI.
9. Axta Space Corporation.
10. Authors Miga and Re are from Advanced Space.
11. Authors Hopkins and Lim are from Blue Origin.
12. Defense Advanced Research Projects Agency (DARPA).
13. Israel and Gramling, "LunaNet Interoperability Specification Document."
14. Megabits per second; gigabits per second.
15. Williams, "NASA Wants to Put a Massive Telescope on the Moon"; Jep Propulsion Laboratory, "Lunar Crater Radio Telescope: Illuminating the Cosmic Dark Ages," Phys.org, May 6, 2021, https://phys.org/.
16. Gateway is a NASA-proposed future lunar space station important to Artemis lunar surface activities.
17. See chapter 12, Cislunar Supply Hubs, for an example of such a relay node hosting mechanism.
18. In the expanding era of lunar exploration and development, the significance of RF surveys could become a key component of operations on the Moon, ensuring communication security, facilitating scientific research, and safeguarding operational integrity. Furthermore, as lunar activities increase, the potential for interference—intentional or accidental—could grow. RF survey offers a solution to manage and mitigate such interference.

8

Robotics as a Service

Edited by Michael Nayak

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8.1 Introduction and Framing

Other services discussed in this *Field Guide* have referenced Robotics as a Service (RaaS) as a key enabler.[3] Robotics on demand can enable almost every other commercial service on the lunar surface. An in situ resource utilization (ISRU) plant (for example, section 5.2.2) that needs regolith can use a robot loader service instead of self-funding a solution. A foundry manufacturing rail beams (for example, section 6.6) will need its products moved to the construction area and can use robotic transport. The construction and maintenance of launch pads (chapter 9) and lunar rails (chapter 12) are anticipated to require extensive robotic labor. An aging infrastructure hub (chapter 10) can make use of robotic maintenance. Across the work on LunA-10, RaaS emerged as a truly fundamental enabling capability to the commercial lunar economy. It will likely become a commercial requirement for most services in the Lunar Industrial Age to design units with external robotic integration in mind.[4]

RaaS introduces lunar robotic service to the paying user by a labor pay-per-use model. A user will not need to consider the maintenance and operation of the robot. A general-purpose robot used for multiple objectives and shared across various services will reduce the number of robotic systems required and provide a mass efficient solution.

As a RaaS provider under LunA-10, robotics company GITAI introduced two types of robots: the Inchworm and the Mover. This chapter introduces the RaaS cost calculation model for these robots and discusses three case studies to show how RaaS operations can be used in a technically feasible way.

To bootstrap lunar infrastructure and not constantly pay to resupply new units from Earth, designing future lunar factories or vehicles to be compatible with robotic maintenance, robotic unpacking, or robotic assembly—or all three—offers significant advantages.

8.2 Overview of Robotics as a Service (RaaS)

Versatile lunar robots can enhance, streamline, and integrate commercial lunar activities. A selection of these applications will be explored in greater detail in this chapter.

8.3 Two Robotic Interfaces for the Moon: Inchworm and Mover

Two types of robots are proposed to provide labor on the lunar surface. The *Inchworm* robot can function as a robot arm, "walk around" by grappling a fixture with its end effector, and perform tool changes. A similar type of robot has been used on the International Space Station.[5] The Inchworm is shown in figure 8.1. The *Mover* robot has four wheels and can be mobile on the lunar surface and will contribute to the "last mile" transportation problem. The main specifications of each robot are shown in table 8.1. Both have an internal battery, a heater to operate during lunar night, and wireless communication devices for control.

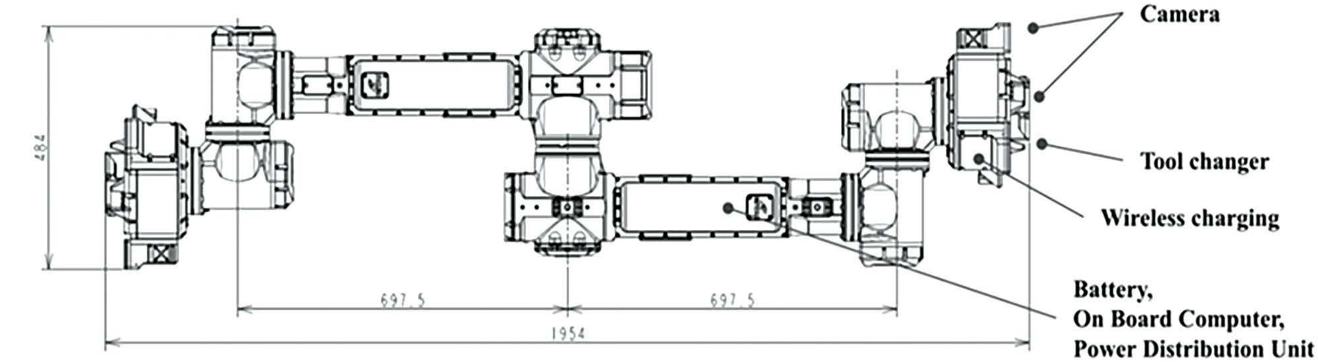

Figure 8.1. The Inchworm robot. [Credit: GITAI]

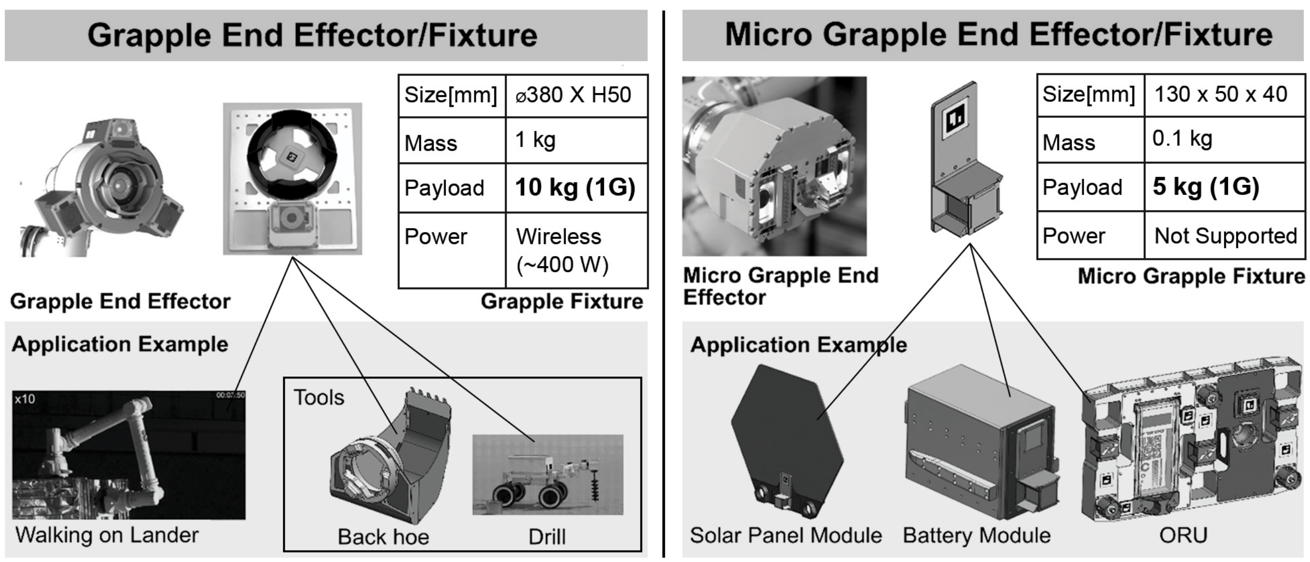

Figure 8.2 Specification of grapple fixtures. [Credit: GITAI]

Table 8.1. Specifications of the Inchworm and Mover robots. [Credit: GITAI]

Specs	*Inchworm robot*	*Mover robot*
Service	Offloading, inspection, assembly, repair, excavation, connecting, cleaning, refill	Logistics, construction, exploration
Size	2.0 [m], (Total 7DOF + 2 end effector)	W 1.5 m x L 1.5 m x H 1 m
Power consumption	120 W (+ 80 W: heater) = 200 W max. (Built-in battery charging: 400 W)	200 W (+ heater) = 440 W max. (Built-in battery charging: 42 v, 20 A = 840 W)
Mass	60 kg	200 kg
Payload	60 kg (on lunar surface)	300 kg (on lunar surface)
Network	Wi-Fi (+ 3GPP) Autonomous: 50 [Kbps]–1 [Mbps], Semiautonomous: 1–30 [Mbps], Teleoperation: 10–50 [Mbps]	
Speed	Walking 0.5 m/s	Driving 5 km/h

Key
DOF: degrees of freedom
3GPP: third-generation partnership project
Kbps: kilobytes per second
kg: kilogram
km/h: kilometers per hour
Mbps: megabytes per second
m/s: meters per second
W: Watt

There are three control types for robotic operations: autonomous control,[6] semiautonomous control (supervised autonomy),[7] and teleoperation control. Autonomous control has the smallest data requirement (1 Mbps) because it only requires telemetry and commands. Semiautonomous control requires image communication and has a data requirement of 30 Mbps. Teleoperation requires 50 Mbps for video streaming. If the network latency is longer than two seconds, teleoperation control will be negatively impacted; during LunA-10, this emerged as a key metric for commercial surface area network or communications services.

Table 8.2. Summary of robotic control requirements. [Credit: GITAI]

Feature	*Autonomous control*	*Semiautonomous control*	*Teleoperation control*
Suitable tasks or services	Simple and repeating task (e.g., logistics, inspection, excavation)	Complex task with several processes (e.g., construction, desconstruction)	Complex task or dealing with flexible material (e.g., repair, explore)
Latency requirement	No impact by latency	Fewer is better, but no limitation	Less than two seconds
Data requirement	50 Kbps–1Mbps (commanding, telemetry)	1–30 Mbps (commanding, telemetry, and images)	1—50 Mbps (video streaming for operator)

Checking with the operator is a costly process. To increase the autonomous rate, a robotic interface can be used by the Inchworm robot. As shown in figure 8.2, a compatible grapple fixture can handle heavy objects, and the Inchworm robot can walk using it as a fulcrum. The grapple fixture also has a wireless power supply function for extended operations. Also shown in figure 8.2, a micro grapple fixture is a small robotic interface suitable for dexterous tasks. These fixtures are equipped with fiducial markers and can be positioned automatically by robot vision.

Next, three use cases are discussed, to better flesh out the specifics of RaaS, together with a discussion of inputs, outputs, limitations, and metrics.

8.4 Use Case 1: ISRU Oxygen Generator Construction and Maintenance

ISRU is currently the "anchor tenant" for the lunar economy. This use case focused on identifying specific robotic tasks to support ISRU, assessing the technical feasibility of such tasks and their economic viability. The primary roles of RaaS to support ISRU were found to be *construction* of the system after launch, *operation* of the system by loading regolith and removing slag, and *maintenance* of the system. Figures 8.3 and 8.4 summarize this RaaS use case.

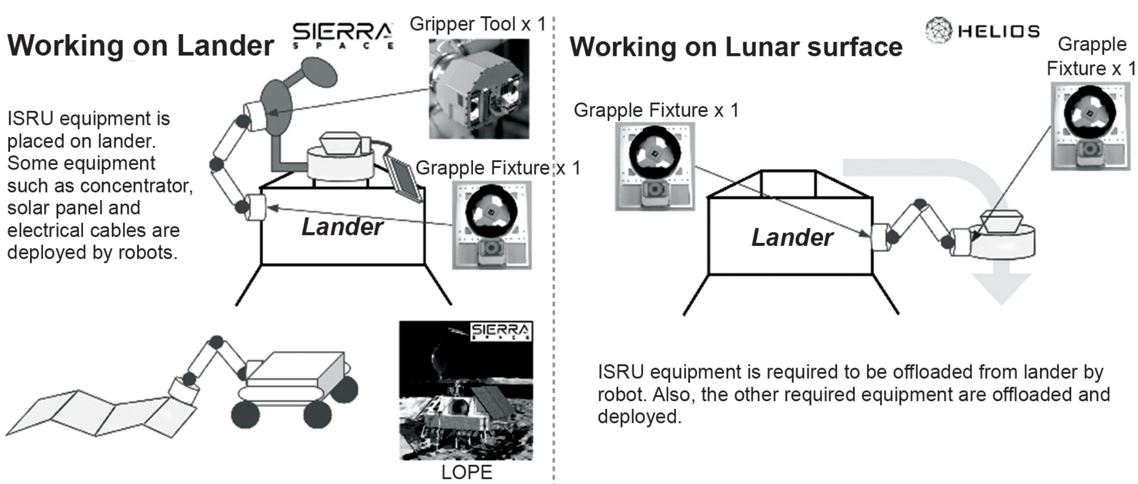

Figure 8.3 Use Case 1, Concept of operations for RaaS-centered ISRU construction and operation, part 1: (left) ISRU equipment is placed on lander. Some equipment, such as concentrator, solar panel, and electrical cables, is deployed by robots. To work on the lunar surface (right), ISRU equipment is offloaded from the lander by robots and placed onto the Mover. The other required equipment is offloaded and deployed. Sierra Space and Helios are notional partners in this process. [Credit: GITAI]

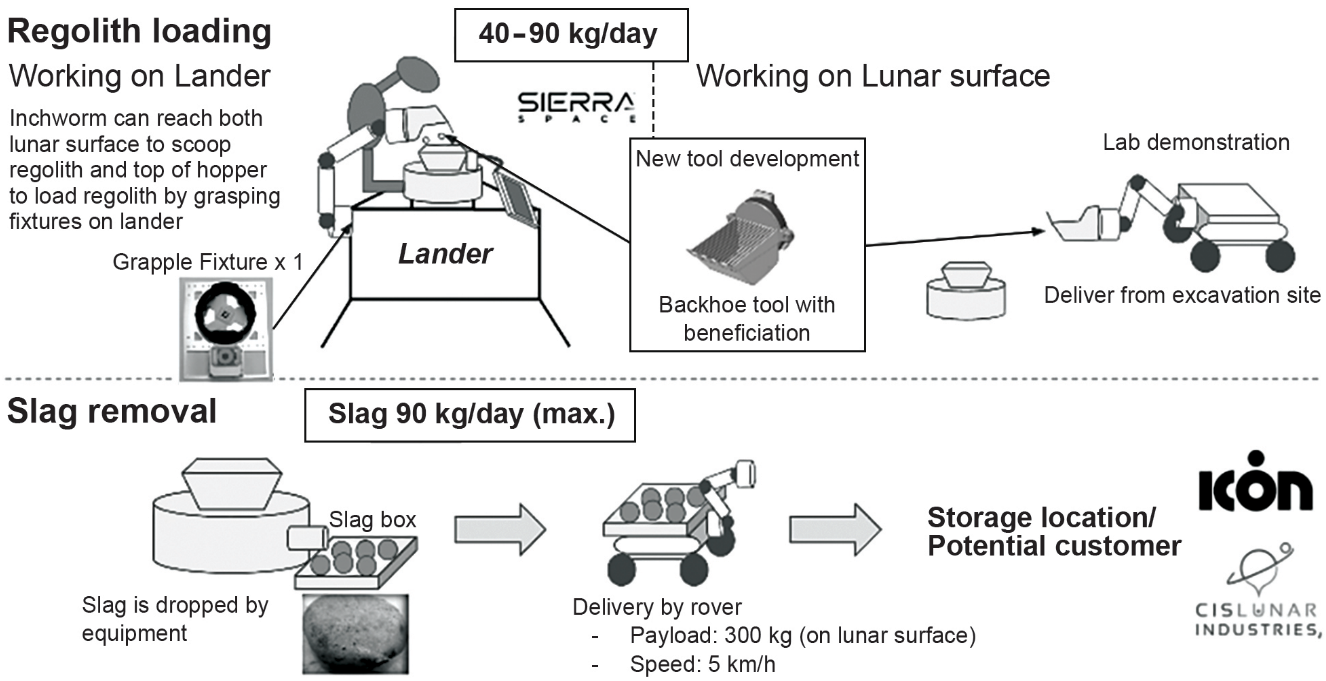

Figure 8.4. Use Case 1, Concept of operations for RaaS-centered ISRU construction and operation, part 2: (top) For regolith loading, the Inchworm can reach both the lunar surface to scoop regolith and the top of the hopper to load the regolith, using grasping fixtures on the lander. (Bottom) For slag removal, the slag dropped by equipment is delivered by Mover robot to a storage location or a potential customer. ICON and CisLunar Industries are notional partners in this process. [Credit: GITAI]

1. Construction. The robot is integrated to the lander via a grapple fixture to enable deployment and operation. A single Inchworm robot and a Mover as a support robot are sufficient.

2. Operation. The main operations are the replenishment of regolith and the removal of slag (DOR). Regolith and slag are approximated at 40–90 kg/day and 90 kg/day maximum, respectively. This can be achieved by developing a backhoe tool to be attached to the Inchworm. A size selection function added to the backhoe tool beneficiates during the scoop operation. The Mover can transport slag or other products directly to the potential customer, contributing to further resource recycling.

3. Maintenance. Maintenance of ISRU equipment includes parts replacement, regolith clogging removal, visual inspection, and similar tasks.

8.5 Use Case 2: Refueling LOX from ISRU to Launcher System

A primary application of ISRU oxygen is as propellant in refueling lunar launchers. This entails the liquefaction of oxygen and its transfer through hoses to launch vehicles such as SpaceX's Starship. The lunar environment necessitates precise positioning adjustments for hose connections, a task well matched to robotic mechanisms. Figure 8.5 summarizes this use case.

It is assumed that the outer wall of the launcher features a grapple fixture. Assuming that the connector between the hose and the supply port is on the ISRU device side, the distance the connector must bridge to the launchpad is about 50 meters.

- Two Inchworms are mounted on one Mover, and the connector is held by one of the Inchworms while it moves to the launcher.
- To inspect the supply port and clean it, two Inchworms climb up to the supply port located 10 meters above the ground while carrying the cleaning tools in a relay system.
- Inchworm robots return to the ground, hold the connector again, carry it to the supply port in a relay system, and attach it to the supply port.
- When disconnecting, two Inchworms climb up to the supply port and carry the connectors and hoses to the ground in a relay.
- Finally, the Mover travels 50 meters back to the ISRU equipment.

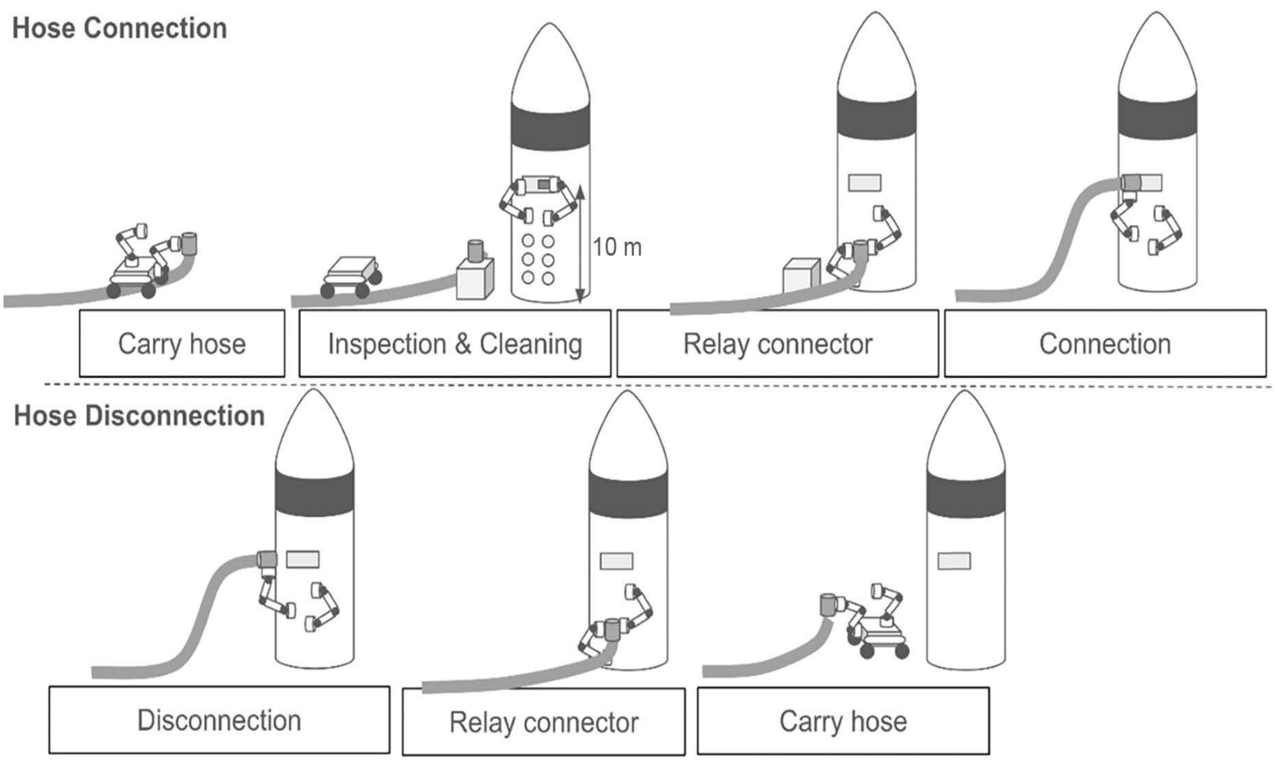

Figure 8.5. Use Case 2: Concept of operations of refueling LOX for a launcher: Inchworm and Mover robots work in tandem to conduct the required tasks. [Credit: GITAI]

The grapple fixtures are mounted on the wall of the launcher to provide power supply to the Inchworms. Twenty fixtures are needed for a total distance of 10 m. Fiducial markers will be added to the supply ports for alignment. The connector should be equipped with a lock/unlock mechanism designed for robots to use. Two grapple fixtures are attached to the connectors to allow them to be carried by relaying. The effectiveness of the relay method using Inchworm has been verified through real-world experiments (for example, fig. 8.6).

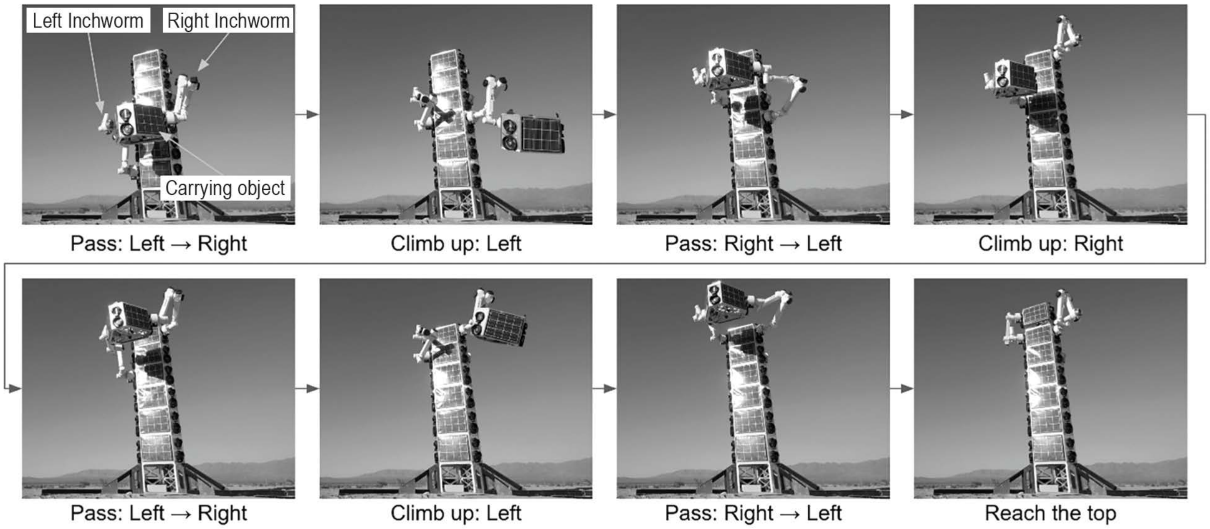

Figure 8.6. Real-world test of vertical logistics by relaying objects with multiple robots. [Credit: GITAI]

8.6 Use Case 3: Recycling Metals through Lander Deconstruction

This use case examines the deconstruction of used landers and other equipment, proposed for a lunar metal recycling ecosystem (chapter 6). By integrating robotic technology, this approach aims to foster sustainable development, reducing the need for material export from Earth. LunA-10 studied the technological requirements for robots to dismantle used landers effectively and provide their materials to a metal recycling plant. A real-world laboratory demonstration, funded by LunA-10, was successfully conducted to assess the robotic dismantling and transportation of lander-derived metallic material. Figure 8.7 summarizes this use case.

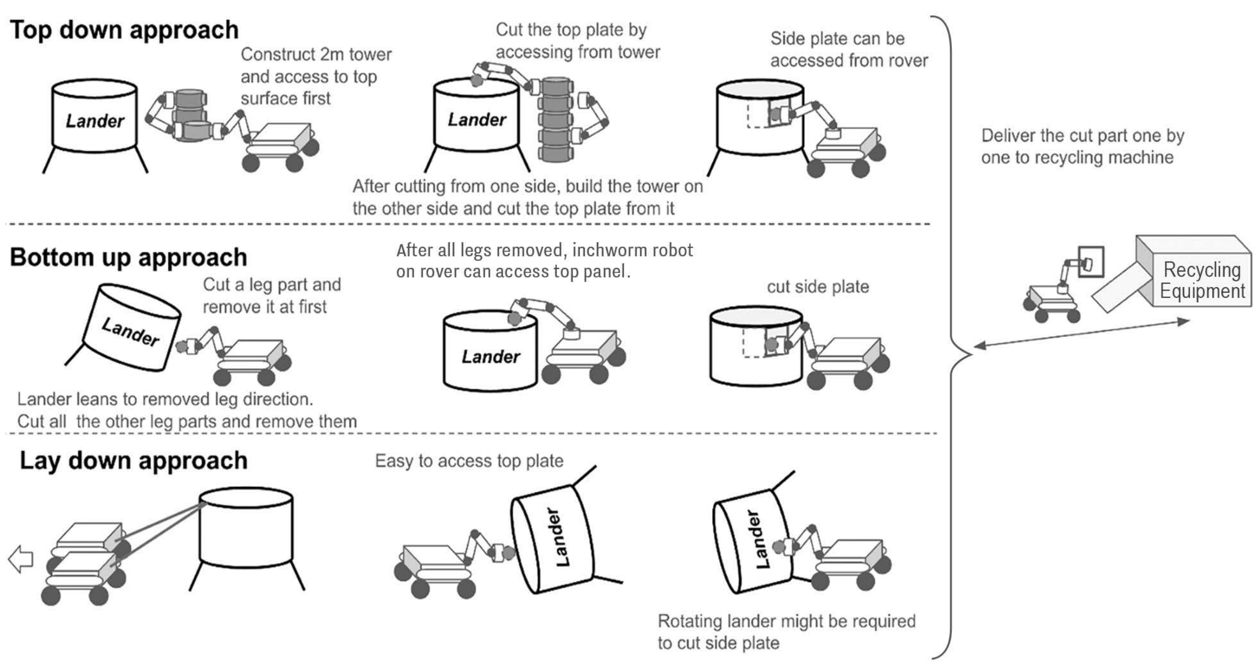

Figure 8.7. Use Case 3: Concept of disassembly of a lunar lander. [Credit: GITAI]

The lander was assumed to be the size of a Commercial Lunar Payload Services lander, and one Inchworm and one Mover are used. The Inchworm, as a cutting tool, extracts a series of 200 mm x 200 mm x 5 mm pieces from the mock-up lander. For aluminum, 200 mm x 200 mm x 5 mm is around 0.5 kg, so the estimated cost to bring this material from Earth would be $500K.[8] That cost is significantly more expensive than the RaaS cost for this task of repurposing the material (RaaS cost estimated in section 8.7). The ratio of RaaS cost to the transportation cost from Earth suggests this may be an economically effective service.

Several possible approaches to disassemble an entire lander, shown in figure 8.7, were studied extensively, to include robotic path planning and optimization algorithms. The bottom-up approach has the advantage in RaaS cost (less time for robotic labor), but there is a risk that the lander may fall in an unexpected direction when the leg is removed, and the robot may be damaged. The lay-down approach is technically difficult, as the traction force is highly dependent on the regolith. The top-down approach is recommended.

In the future, it would be effective to reflect the disassembly of the lunar surface in the design of the lander. For example, an explosive bolt could be installed to automatically dismantle the lander. Since the design cost of such a cooperative lander would be high, a grapple fixture on the outer surface of the lander would allow access to the top of the lander. This eliminates the need to construct a tower, which accounts for a quarter of the RaaS cost for the top-down approach.

8.7 Commercialization

A simple methodology for calculating the "$/hour" cost of RaaS was developed under LunA-10. Next, the time needed for each task is estimated, allowing a computation of the overall cost in "$/service."

For the calculation of task time, it is hypothesized that the tasks of all robots are a set of basic robot operations such as "pick and place." All tasks can be decomposed to basic robotic operations to calculate the time required, shown in table 8.3. This is based on the robot's current demonstrated capabilities, with no further advances to the state of the art required.

For the RaaS fee per unit of time, business analysis conducted under LunA-10 sets the $/hour as $20,000/hour for the Inchworm robot and $40,000/hour for the Mover robot. Based on a proprietary recapitalization model, the initial investment to deploy these robots to the Moon can be recovered in two years under realistic operation rates, generating profit after that.

Table 8.3. Basic robot operations

Basic Robot Operation	*Time [min]*	*Unit*
Pick	5	Per part
Move (by Inchworm robot)	3	Per part
Place	5	Per part
Logistics (Mover)	12	Per km (5 km/h)
Scoop / Pour	5	Per scoop
Other special action	(Depends)	E.g. wipe
Walk	3	Per step

There are several technical challenges that must be overcome to maximize benefits for RaaS as an enabler of the lunar economy:

- Increase autonomous rate to reduce communication cost and speed up robotic actions. The primary control method is currently semiautonomous, but operator confirmations slow down tasks.
- Deal with heavy objects. Increasing the power of the robotic motors can increase transportation fees to the Moon (e.g., doubling the motor power leads doubles the mass of the robot).

Development of large construction tools can also be challenging; high uncertainty of the usage rate and requirements makes recapitalization prospects risky.

- Build network infrastructure during the scaling phase. This poses a technical challenge due to a chicken-and-egg situation: RaaS requires a network to operate, yet the construction of this network depends on RaaS itself.

8.8 Conclusion

This chapter covered how RaaS can contribute to the lunar economy from both a technological and economic aspect. Three case studies showed that combining an Inchworm and Mover robot can offer the versatility needed to functionally establish the lunar economy. The next step involves ground demonstrations to validate the system's feasibility and verify the accuracy of estimated task times to calculate the RaaS cost. Significant real-world validation work has already been done, which shows that RaaS can be deployed in the near term and scale with the size of the future commercial lunar economy.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Shibata, Terada, Ueda, Kozuki, and Nakanose are from GITAI USA Inc.
2. Defense Advanced Research Projects Agency (DARPA).
3. Kapitonov et al., "Robot-as-a-Service"; and Chen et al., "Robot as a Service in Cloud Computing."
4. See chapter 14 for more details on the Lunar Ages.
5. King, "Space Servicing: Past, Present and Future."
6. Autonomous control is fully automatic, so the operator only needs to confirm the start and end of the task.
7. Semiautonomous control is an intermediate control method that checks the operator at important scenes in each task segment.
8. Commercial estimate (Astrobotic Inc.) for payload to the surface of the Moon, current as of May 2024, \$1M/kg.

9

Commercial Landing Pads for Heavy Landers

Edited by Michael Nayak

Contributing authors: Evan Jensen, Lucas Laughery, Cody Bressler, Ian E. Jehn,[1] and Michael Nayak.[2]

9.1 Introduction and Framing

When considering infrastructure on the Moon, neglecting landing pads would be like asking a Boeing 767 to land on a beach instead of a runway every time. Rocket plume exhaust impinges high pressures and temperatures to the landing surface that can create cratering, lofting, and transport of regolith particles at high speeds.[3] High-velocity ejecta composed of regolith particles can reach ballistic trajectories greater than 2,000 meters per second (m/s) and can travel large distances in a vacuum.[4] This can damage the vehicle structure, engines, or anything in the vicinity. For example, damage from ejecta to the Lunar Surveyor III lander was measured at 155 m from the Apollo 12 landing site.[5] Landing pads, such as those detailed in this chapter, can incorporate a form of regolith stabilization to mitigate this impact and provide safe, reliable landing zones. [6]

The reduced efficiency of sensors and visibility caused by the resulting regolith dust cloud is also a major concern.[7] The system concept and analysis in this chapter review a notional design for a lunar landing pad to support a SpaceX Starship lander. The pad will be created using in situ material and ICON Technology's laser vitreous multi-material transformation (VMX) construction system, a 100 percent in situ resource utilization (ISRU)–based solution to create structural elements from raw lunar regolith.

If such landing pads existed, they would be a natural termination point for the lunar rail system discussed in chapter 12, particularly if protective berms were constructed. The rail would then transport the ~10–100 tons of lunar payload delivered by a heavy-lift lander from the point of delivery to the point of need. Furthermore, just 10 km away would be a natural location for a Lunar Oasis or LunarSaber node (chapter 10), with associated power (chapter 4); data, communications, positioning, navigation, and timing (Comms/PNT) (chapter 7); light, thermal, and other services. This is discussed further in the architecture segment of this book (chapter 14). **Landing pads would increase accuracy and repeatability of safe landings to regions of high economic activity, making them a core unit of a scalable commercial lunar infrastructure.**

9.2 Background and Methods

The laser VMX lunar construction system brings the raw regolith through a full melt cycle, applying a context-sensitive thermal schedule using directed energy to produce structural elements. The resulting crystalline material has favorable strength properties. When combined with robotics, the process is capable of 3D printing horizontal and vertical structures using only locally sourced regolith as feedstock (100 percent ISRU).

The system autonomously scoops, sieves, compacts, and lases, resulting in high-performance structural elements across many scales and arbitrary geometries. Testing and analysis show that all VMX landing pads can survive the thermal conditions of the lunar south pole and withstand the expected heat flux generated during landing of a human class lunar lander. NASA's Moon-to-Mars Planetary Autonomous Construction Technology Project corroborated these findings and selected laser VMX as the primary process for its additive construction needs.[8]

The ICON laser VMX system is at a Technology Readiness Level of 6 (on a scale of 1 to 9) as of this writing, with a lunar demonstration possible as soon as 2027. Off-lander construction systems and possible integration with lunar terrain vehicles could follow as soon as a year after.

9.3 Technical Approach

For safe landing, it is suggested that a Starship pad be designed with a minimum radius of 60 m (120 m diameter). Lander scale and loading are expressed as follows:

- Landing craft is approximately 9 m in diameter
- Assume the plume area of effect to be the same. At a 10m radius from the vehicle centerline, the pressure is below 10 percent of the peak pressure.
- Minimum plume pressure = 300 kiloPascal (kPa)
- Maximum plume pressure = 1,700 kPa
- Lander legs have 2.1 m2 diameter footpad
- Legs located 8 m from the vehicle center line
- Minimum footpad pressure = 30 kPa
- Maximum footpad pressure = 70 kPa

The structural difference between grades of VMX product is the porosity of the sintered material. Grade 1 has the highest amount of porosity, and Grade 3 has the least. A Grade 3 VMX material is highly dense and crystalline, resulting in a low coefficient of thermal expansion (CTE) structural ceramic material. Properties used in the analysis are as follows:

- Compressive strength = 345.0 megapascals (MPa)
- Tensile strength = 17.3 MPa
- Modulus of elasticity = 68.9 gigapascals (GPa)
- Density = 2.6 grams per cubic centimeter (g/cm^3) (2,600 kg/m3)
- Poisson's ratio = 0.25
- CTE = 4.0×10^{-7} °C-1

As in terrestrial structural engineering design, to address the landing pad design, loads are designated into categories. Dead loads (D) consist of the actual weight of all materials in the pad as affected by lunar gravity (1.62 meters per $second^2$). Live loads (L) are applied loads induced on the structure by the rocket plume and vehicle lander legs. In addition to both live and dead loads, loading from both the landing craft plume and the lander legs is also applied.

A layer of regolith subgrade will provide vertical support to the landing pad. This support has been modeled as a series of springs with a specified stiffness. This is a typical terrestrial procedure for foundation design. The geotechnical term for the stiffness of the regolith is the *modulus of subgrade reaction*, which describes the deformation behavior of soils when vertical pressure is applied. It increases with an increase in soil density. Thus, it is typical in terrestrial construction to compact the site's soil to increase this modulus, which decreases the amount of vertical deflection when the foundation is constructed. This provides increased support and bearing capacity, reducing the required pad thickness.

Another way of measuring a soil's level of compaction is *relative density (D_r)*, the ratio of a soil's density to the maximum density of that same soil obtained in laboratory conditions. It is common terrestrially for a subgrade to be prepared to a 90 percent D_r before a foundation is constructed on it. Values for these quantities for the Moon can be found in the Lunar Sourcebook.[9] If the native lunar surface is prepared via compaction, a stiffer subgrade results. This provides increased support and bearing capacity, which can reduce the required pad thickness and therefore the time to construct it. The required compaction depth is the distance into the lunar surface until the indicated D_r is naturally achieved. This means this depth of the surface needs to be either prepared or removed to provide the indicated modulus of subgrade reaction.

Table 9.1 presents the required compaction depth by indicated D_r. Assumed values of modulus of subgrade reaction to the increased levels of D_r are shown.

Table 9.1. Distance into the surface to naturally achieve the desired relative density

Surface preparation (compaction) to relative density (D_r)	*Required compaction depth (cm)*	*Assumed corresponding modulus of subgrade reaction (kPa/m)*
No preparation	-	1,000
60%	2.5	1,333
70%	3.9	1,667
80%	6.7	2,167
90%	15.1	2,800

The model includes five regolith profiles (no preparation, 60 percent D_r, 70 percent D_r, 80 percent D_r, and 90 percent D_r) to determine the relationship between surface compaction and landing pad thickness. Figure 9.1 shows example soil bearing stress results for a 150 mm pad with 90 percent D_r subgrade. This shows how much pressure is transmitted into the regolith below through the pad material.

Four load cases were applied to these five regolith stiffness profiles. Loads were computed for a center-nominal landing and an off-nominal edge-landing and with both Dead and Live loading, or D+L. The four cases are as follows:

1. 1.0D + 1.0L (plume pressure at center of pad)
2. 1.0D + 1.0L (plume pressure at edge of pad)
3. 1.0D + 1.0L (leg bearing at center of pad)
4. 1.0D + 1.0L (leg bearing at edge of pad)

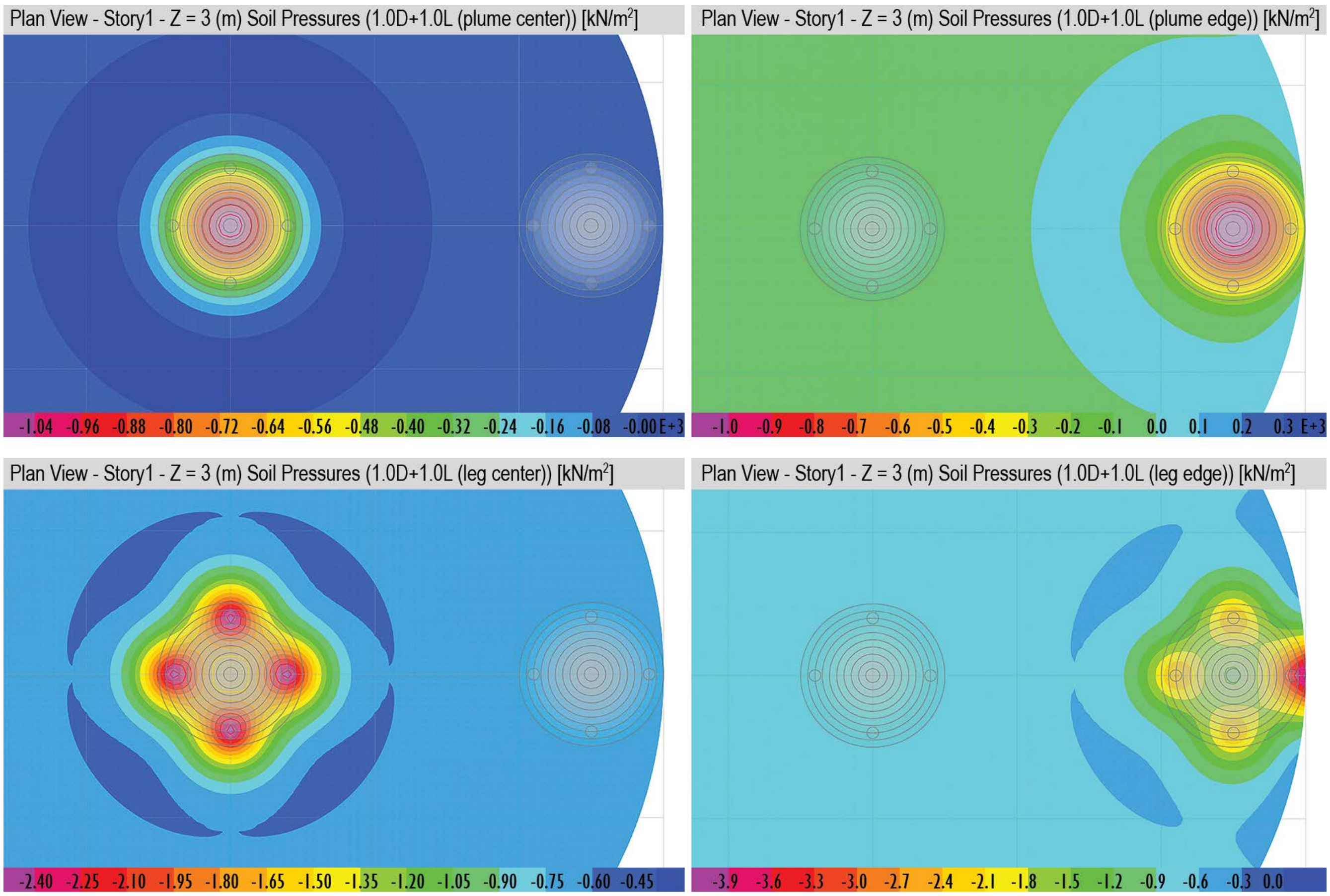

Figure 9.1. Example soil pressure results for 150 mm pad with 90 percent D_r subgrade. Secondary landing loading shown in gray is for context only and is not applied to the soil conditions. [Credit: ICON]

Within each of these cases, the pad thickness was varied to determine resulting stresses, deflections, and soil pressures. Tensile stresses far outweighed the tensile strengths. Thus, the pad system will crack on the bottom (tension) side of the pad. The maximum compressive stress results after this equalization.

In terrestrial structural engineering, this is called "compression-controlled" design and is common in slab-on-grade design procedures. The required thickness of the pad for each regolith profile, using the four load cases, was determined. Plume loading controlled the design by a significant margin (typically two orders of magnitude difference in compressive stresses).

This resulted in thick pad requirements, with large anticipated vertical deflections. Table 9.2 provides a summary of the parametric design envelope of the pad design. Multiple thicknesses were evaluated to produce an analysis of the stress demand versus capacity relationship. Resulting anticipated maximum vertical deflections and soil pressures are provided by thickness. These pressures are extremely high due to the conservative nature of the analysis and will need additional evaluation in the future.

Table 9.2. Values in the pad thickness parametric study, summarizing all designs run. Compression strength is 345 MPa; tensile strength is 17.3 MPa. [Credit: ICON]

Note Load Cases		***Plume Pressure***				***Leg Impact***			
Surface D_r (%)	*Pad thickness (mm)*	*Maximum compressive stress (MPs)*	*Maximum tensile stress (MPs)*	*Maximum vertical pad deflection (mm)*	*Maximum soil pressure (kPa)*	*Maximum compressive stress (MPs)*	*Maximum tensile stress (MPs)*	*Maximum vertical pad deflection (mm)*	*Maximum soil pressure (kPa)*
No preparation	150	1371.1	Bottom side cracked = 17.3	671.4	499.2	9.4	9.4	3.2	3.9
	300	795.6		263.4	292.4	2.4	2.4	2.8	3.1
	610	**339.8**		**188.9**	**190.2**	**0.8**	**0.8**	**2.6**	**2.8**
60%	150	1212.8		413.1	550.6	7.6	7.6	2.7	3.8
	300	738.8		237.6	317.5	2.3	2.3	2.3	2.9
	565	**345.0**		**174.7**	**232.6**	**0.8**	**0.8**	**1.9**	**2.7**
80%	150	953.6		347.7	659.5	6.1	6.1	2.4	3.5
	300	631.3		204.1	437.4	2.1	2.1	1.8	3.1
	520	**344.8**		**148.1**	**316.3**	**0.9**	**0.9**	**1.6**	**2.8**
90%	150	836.9		329.2	750.8	5.9	5.9	1.8	3.4
	300	580.3		196.5	537.1	2.0	2.0	1.5	3.1
	485	**344.9**		**136.2**	**381.1**	**0.9**	**0.9**	**1.2**	**2.6**
Typical controlling load case		Plume at center	Plume at center	Plume at edge	Plume at edge	Leg at center	Leg at center	Leg at edge	Leg at edge

9.4 Scaling Study

Timelines for production of various landing pads and the scaling of pad production were studied and parameterized. Figure 9.2 reflects the laser VMX landing pad production versus time for various pad classes, given 1 cm average thickness. Smaller pads can be produced in less than one year, given a single landing and robot. Larger pads, such as for a reusable Starship, require robotic parallelism to bring production to reasonable timescales. Laser processing is set at twenty-five minutes per cycle, for a 78.9 percent duty cycle. Laser optical-to-electrical efficiency was set to a standard value of 40 percent.

The values provided in white circles (fig. 9.2) are monolithic pad diameters run with the settings in section 9.3 and structural volume assumptions with a 1 cm thickness. Wattage input to the charging system factors into robotic motion estimates and time-based concepts of operation. The dotted lines below 1,000 W are likely not viable, as the laser heat flux on the regolith is insufficient to run the VMX process. Missions below that power become nonviable financially as well, as they take too long to produce.

The material produced per laser-watt scales monotonically, with a low-end heat flux requirement and a high-end thermal limit on the laser diode arrays. More power will yield more throughput. Since the robotic motion (duration and associated power usage) does not change as power goes up, a linear relationship emerges between material produced and energy consumed for a given operational duration.

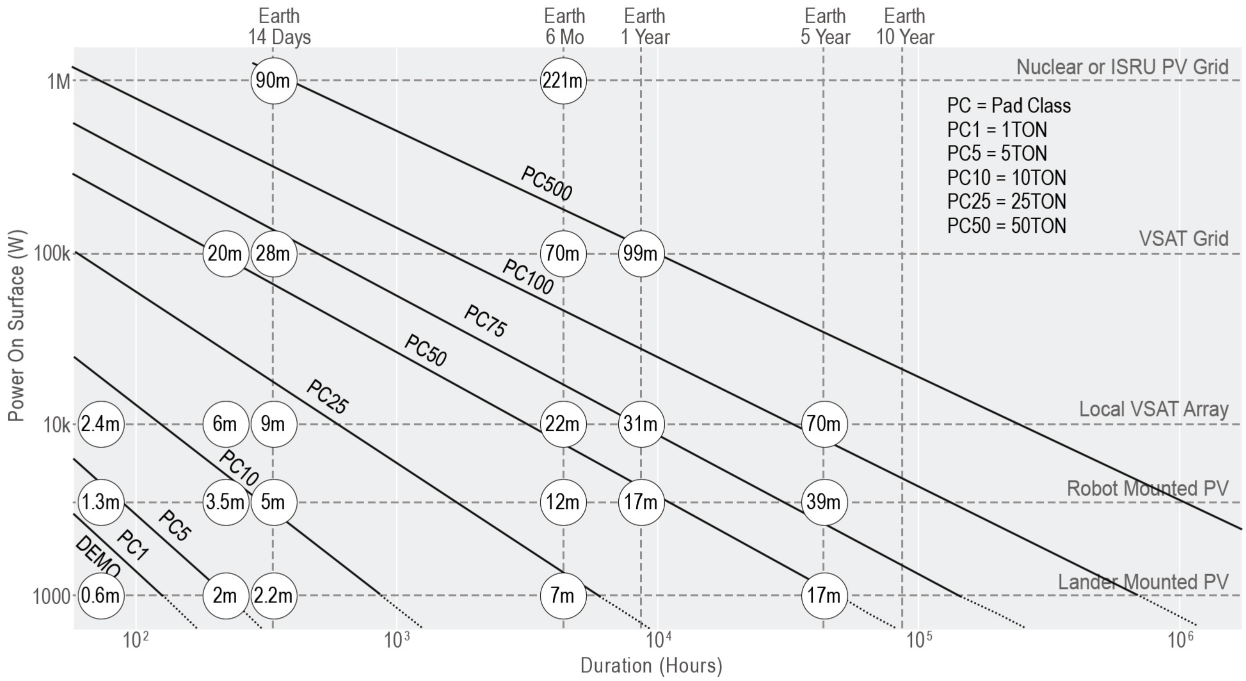

Figure 9.2. Pad production versus power-on surface and time. [Credit: ICON]

However, if the robotic motion component (digging, filtering, tamping) remains with a constant ratio to time spent lasing, then as laser power increases, a benefit in throughput is seen, because more work is being done while in the lasing state. Figure 9.3 shows a range of powers from 1 kW to 8 kW; a decrease in embodied energy per kg of produced material is noted.[10]

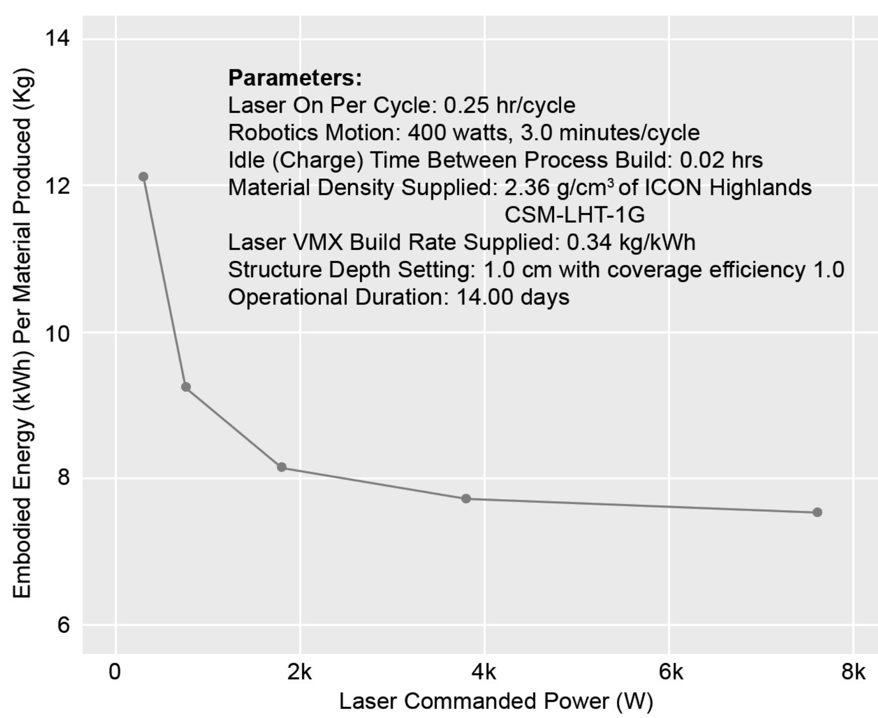

Figure 9.3. Laser VMX embodied energy (kWh) per kg material produced vs. laser commanded power (W). [Credit: ICON]

This is because power draw is primarily a function of the number of laser diodes on the end effector. Using more laser diodes allows for a larger laser swath at the expense of more weight and power draw. The addition of a second laser in a serial positioning orientation, following behind on the same layer of VMX material, will increase overall process efficiency and provide redundancy.

9.5 Conclusions

Using laser VMX to pave roads and landing pads is feasible today and maximizes the resource-efficient inputs of raw regolith, since the system requires minimal materials launched to the surface. The current production time estimate is roughly one month for a 10 m diameter landing pad, with 10 kW surface power supplied. There is a critical link between construction and power, particularly wireless power as the sintering unit moves around the pad it is creating.

The same principles hold for road construction at or around infrastructure hubs, explored in the next two chapters. The strategic use of laser VMX to create 100 percent ISRU infrastructure can drastically increase the throughput (with enabling power) and drive cross-mass logistics on the Moon's surface for the future lunar economy.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Jensen, Laughery, Bressler, and Jehn are from ICON Technology Inc.
2. Defense Advanced Research Projects Agency (DARPA).
3. Mehta et al., "Thruster Plume Surface Interactions"; and Mantovani et al., "Launch Pad in a Box."
4. Kelso et al., "Planetary Basalt Field Project"; and Metzger, "Dust Transport and Its Effect."
5. Immer et al., "Apollo 12 Lunar Module Exhaust."
6. Mishra et al., "Effect of Lunar Landing on Its Surface."
7. Gelino et al., "Off Earth Landing and Launch Pad Construction."
8. NASA Marshall Space Flight Center, "Moon to Mars Planetary Autonomous Construction Technology."
9. Heiken et al., *Lunar Sourcebook*.
10. Note that this relationship is possibly incorrectly amplified by an assumption in the model that it takes the same time to prep a surface for 1,000 watts of laser-time as it does 8,000 watts of laser time, yet the throughput overall goes up.

10

Lunar Infrastructure Hubs

Edited by Michael Nayak

Contributing authors: Vishnu Sanigepalli, Richard Margulieux, Nicholas Naclerio, Roe Burrell, Dean Bergman, Kris Zacny, Kayla Klein, Lily Clay, Zachary Begland, Kevin Hubbard, Grayson Glazer,[1] and Michael Nayak.[2]

10.1 Introduction and Framing

Some of the oldest cities in the world are on the banks of rivers. In the preindustrial age on Earth, rivers allowed movement, shipping, trade, and commerce. Alexandria, Virginia, is older than the capital of the United States and sits on the banks of the Potomac River, for example. Around the world and across history, rivers have enabled resource sharing, turning ports into hubs and villages with ports into major cities. Cities thrive and grow due to the sharing of resources within them, creating a hub that incentivizes commerce.

However, in commercial plans for the Moon today, it is difficult to see an analogous concept. Both government and commercial entities are investing in building one-of-a-kind machines. Each must organically support all the resources they need, that is, their own power, communications, data storage, and so forth. This state of play today is akin to the Moon's exploration age,[3] which means everything one sends there must be completely self-sufficient. There is no lunar infrastructure.

A sustainable lunar economy lives in what's more akin to an industrial age, like city living. If one simply purchases power, the lights can turn on. Buy internet and a mission can have data. If infrastructure services exist, all a lunar user must bring is the mission.

LunA-10 hypothesized that the key to building such infrastructure services was *aggregation*. Specifically, "LunA-10 aims to facilitate the fusing and co-optimization of as many infrastructure sectors as possible onto standard payloads that can be delivered to the lunar surface and, in the future, scale up to the size of ubiquitous infrastructure for the Moon."[4] In an analogous manner to how river ports turned into major cities due to growing infrastructure, what technology might catalyze lunar aggregation to host services and encourage further investment in the lunar economy?

This and the next chapter discuss two deployable towered hub systems, LunarSaber and Lunar Oasis, which focus on the consolidation of services to minimize mass and complexity for future users on the Moon. LunarSaber infrastructure provides critical services to surface users such as power and energy storage, communications, and asset monitoring. In chapter 11, Lunar Oasis builds upon LunarSaber by focusing on thermal consolidation, providing commercial heat rejection and generation for surviving extreme temperatures on the Moon. These systems can be deployed for polar, mid-latitude, and equatorial regions of the Moon with reconfigurable, scalable subsystems. Both hub towers stand as examples of the LunA-10 vision: **moving from an era of fractionation to an era of connectivity**. Infrastructure hubs are a cornerstone for lunar infrastructure that provides key services at a fraction of the cost and accelerates the lunar economy for both public and private industries.

10.2 System Overview: LunarSaber Towers

Lunar Utility with Navigation with Advanced Remote Sensing and Autonomous Beaming for Energy Redistribution, or LunarSaber, is a deployable 20-to-200-meter towered structure that integrates energy harvesting and storage; communications; mesh networking; positioning, navigation, and timing (PNT);

power transfer; and surveillance into a single infrastructure node that can provide commercial services to both the public and private sectors. The architecture can scale by size to fit the volume and mass constraints of various landing systems. A hub could also be customized by focusing on just one or more of its capabilities (e.g., focusing on energy harvesting alone), given lunar customer needs.

An insight from LunA-10 is: **Through strategic site selection, a hub tower can generate critical operational power for surviving lunar nights. It can generate power 94 percent of the time, *including* lunar nights**.

The proposed design (fig. 10.1) is 100 m tall with a structural mast diameter of 2 m and a deployed solar bellow diameter of 6 m. An eighty-to-one length-to-diameter ratio has been demonstrated under a Honeybee Robotics program called Deployable Interlocking Actuated Bands for Linear Operations (DIABLO), which developed a novel helical band actuator to store and deploy a rigid tubular mast. Recent analysis and technology maturation have shown upward of one hundred-to-one capability. The 1,000 square meter solar panel area of such a tall tower can generate up to 150 kW of power through the lunar day without interruption. The base battery is sized for 50 kWh storage with a 60 percent depth of discharge to provide power for thermal management and onboard avionics. Such hubs facilitate collaborative resource sharing and provide redundancy for extravehicular activities (EVA) and critical lunar missions.

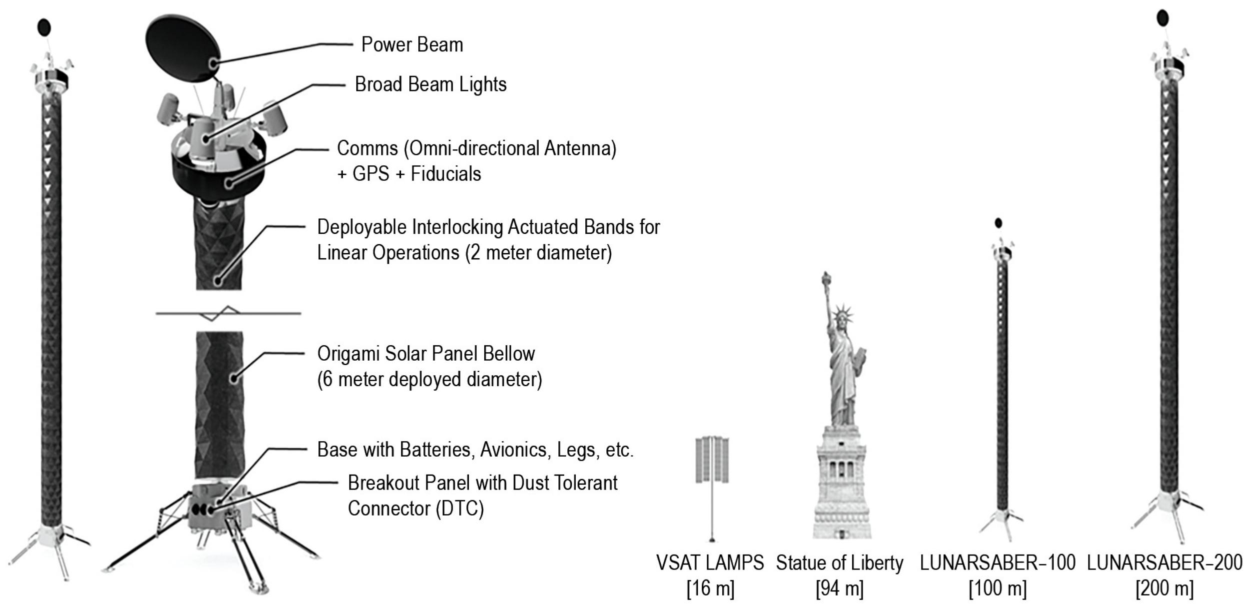

Figure 10.1. (Left) LunarSaber stowed and deployed configurations with subsystem breakdown. (Right) Form factor options. LunarSaber can scale to 100 m and 200 m heights to increase the periods of continuous illumination and shorten periods in darkness. [Credit: Honeybee Robotics]

The subsystems of LunarSaber are as follows:

- Solar bellows. Utilizes origami bellows made of flexible printed circuits (FPC) which enable stowage in a folded configuration for launch. These bellows are deployed by the main mast, DIABLO. The power is transmitted via built-in circuitry within the FPCs to the base and masthead, along with other communications. Since the panels provide a 360-degree field of view, the system can generate power without additional actuation.
- Power beaming with gimbal. Hubs can host assets to beam power to lunar users (see chapter 4) for continuous lunar operations or survival power for thermal, avionics, and communications. The pan and tilt gimbal provides full 360-degree coverage to transfer energy to any asset within line-of-sight.

- Floodlights with gimbal. Provide broad-beam, high-intensity light to illuminate the lunar environment during low light conditions for astronauts, rovers, and other assets.
- Cameras and asset monitoring. Use a 360-degree field of view to monitor the terrain and provide live feed data to lunar bases, Earth, and astronauts during EVAs.
- Communications. Utilize omnidirectional antennas as a node to transfer and process data from lunar assets to the base and can host assets such as MUST-Heavy for communications, positioning, navigation, and timing (Comms/PNT) (see section 7.3). As the number of systems scales, the network can expand to transmit data across large distances, overcoming local and regional topographical challenges. This enables communications from the surface to lunar orbit and line-of-sight communications with Earth with strategic site selections.
- PNT. Provides high-precision unique signal emitters for precise local positioning of mobility systems and astronauts.
- Universal dust-tolerant connector. Provides a power distribution panel for power transfer to surface assets (science payloads, habitats, ISRU instrumentation) and recharges rovers.
- Base with anchored legs. Houses redundant avionics and batteries for energy storage and surviving lunar nights. The anchored legs provide stability margins for moonquakes and thermal shocks during lunar eclipses.

To transfer power to other lunar assets, hub towers would use a two-axis precision gimbaled photonic laser emitter at top of the structure (as high as 200 m tall; fig. 10.1) to photovoltaic array receivers mounted on various lunar assets. This allows for long-range power transmission without the need for heavy harnessing routed in-between multiple systems. By hosting compact and localized PNT systems, hubs can provide position state data for landers, rovers, and astronauts for navigation during critical extravehicular activities over a wider area of regard than normal lander or habitat systems. **Due to the limited view factors inside craters and permanently shadowed regions (PSR), towers provide continuous PNT services that traditional satellite-based architectures struggle to provide**.

The 360-degree field of view cameras and the actuated broad-beam lighting system allow critical asset monitoring to help mission control oversee autonomous robotic systems and extravehicular activities. Hub-hosted communications systems can evolve into a mesh network for communication without line-of-sight. A gimbaled communication antenna at the top of the structure also provides direct-to-Earth communications and can be extended with data storage capability at the base of each hub to serve as a decentralized network to store, transmit, and provide mission data.

There are two different scaling opportunities for a hub tower architecture: form factor and production. As the deployment system increases in diameter and height (fig. 10.1), the power generation scales linearly. These two parameters (diameter/height) can be adjusted based on customer requirements such as power need, launch up-mass, down-mass, and volume capability. Hubs can also be customized for different needs: a “fully loaded” hub can be strategically positioned near crater rims, while hubs for PSRs at the lunar poles can be deployed without solar panels and only used for power transfer, PNT, communications, and asset monitoring. Increasing the number of hub towers also increases the capability to process and transmit data faster across a cross-threaded network. The node network can help offload processing storage using its omnidirectional antenna up to 74 km away, for a 200 m deployment height.

Shackleton crater, at the lunar south pole, is illuminated for >80 percent of a lunar precession cycle, with some locations illuminated at >95 percent (~18.6 years).[5] If deployed at such locations, hub towers would provide near-continuous power for operations and lunar night survival. As the viewshed analysis in chapter 4 shows (section 4.2.5), the system sees an increase in performance with increased height. Power generation would not be at full capacity during ground-level darkness, as the sun would only illuminate the top of the solar panel assembly (while dark at ground level). This paradigm allows power redundancy for self-survival and the enduring capacity to beam power to other assets.

For the short periods in total darkness, the batteries in the base of the system are sized to survive and continue to provide power to other lunar assets. Since the illumination of these regions is deterministic and well-studied, mission architectures can be optimized to recharge and store energy prior to these events.

10.3 Seismic Analysis

A benefit of aggregation is that lunar hubs such as LunarSaber towers become magnets for additional users, as commercial services such as power, comms, and PNT become available. Therefore, it will be best to land future users as close to an infrastructure hub as possible, enabled by landing pads that limit dust clouds on landing (chapter 9). An unfortunate event such as a lander crash can lead to critical infrastructure failure, a low-probability, high-consequence disaster that could wipe out not just one but multiple connected users and services.

Preliminary analysis was done on the crash of a 200-ton heavy-lift lander, impacting the surface of the Moon at 200 meters per second. This would release 4 gigajoules of energy, or 1 ton of TNT. The energy was applied to a lunar seismic model to understand P-wave and S-wave accelerations with distance from the epicenter. The hub tower is modeled as a structurally stiff single-body. Results are shown in figure 10.2.

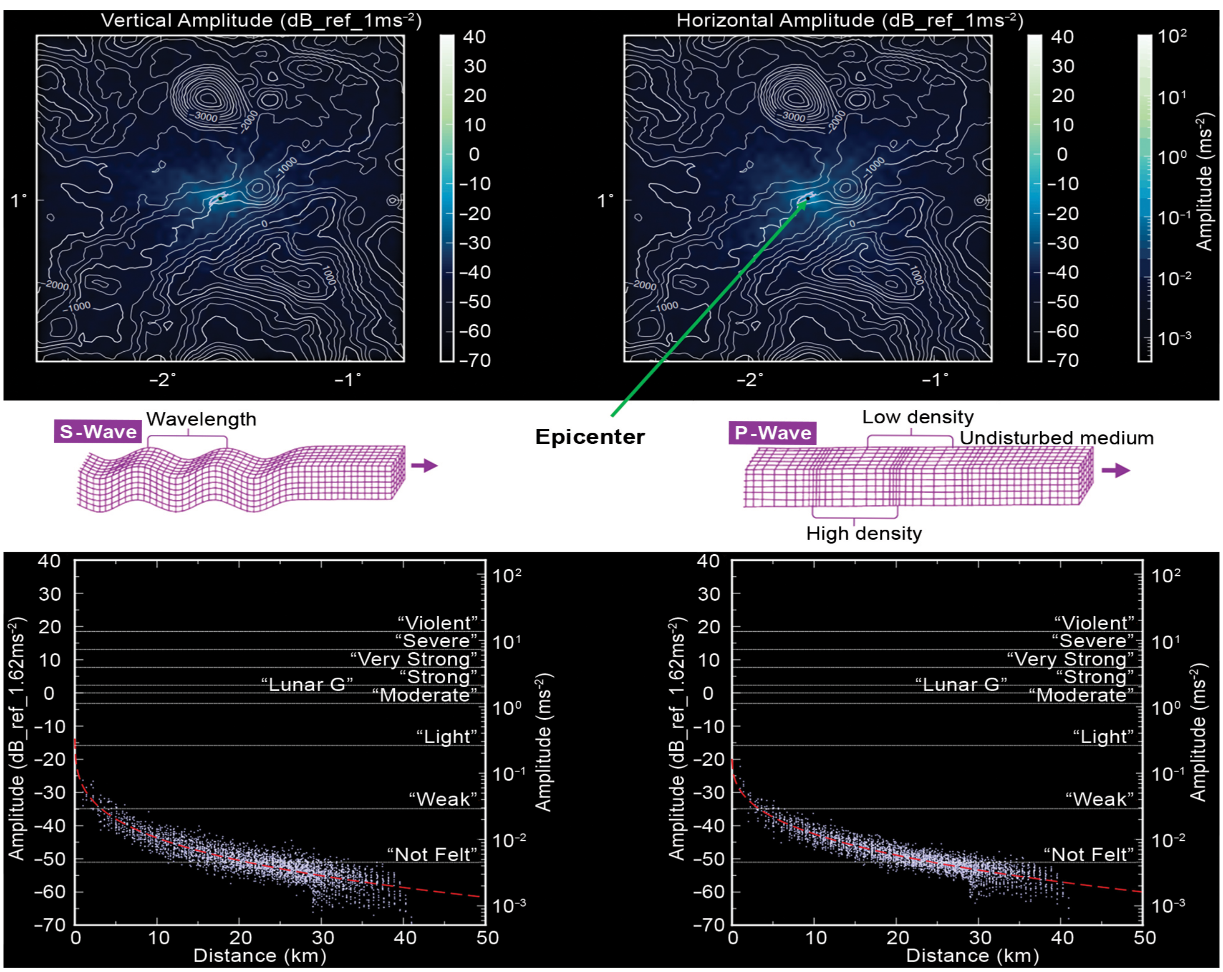

Figure 10.2. (Top) Heat map of S- and P-wave amplitude as a function of distance from the epicenter of crash anomaly. (Bottom) Amplitude of S- and P-waves as a function of distance from the epicenter of crash anomaly. [Credit: Honeybee Robotics]

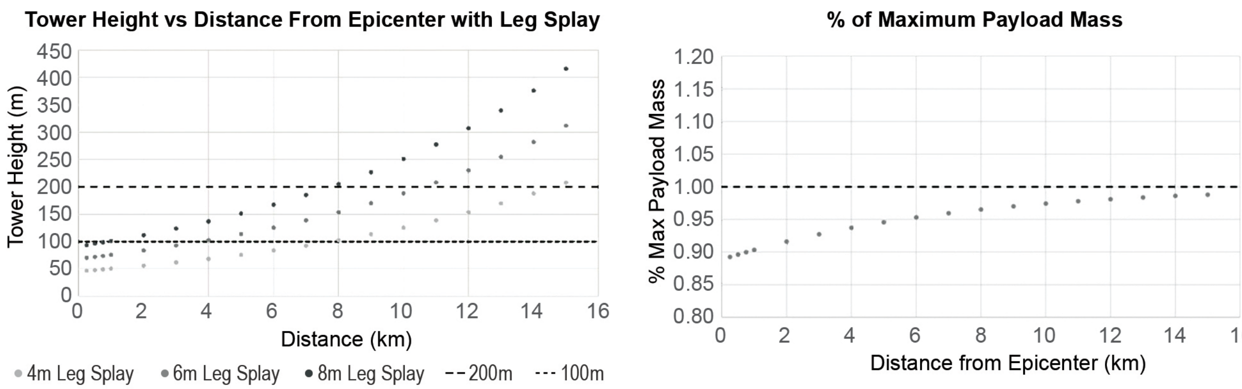

Figure 10.3. (Left) Maximum height for given leg splay (4 m, 6 m, 8 m) as a function of distance from epicenter. Primarily driven by P-waves, this shows that a standoff distance of 10 km for rocket landings should be sufficient to ensure no adverse interactions. (Right) Percentage total mass capacity for a system that has a requirement for surviving a crash anomaly. [Credit: Honeybee Robotics]

A static analysis on the generated P-waves (lateral surface acceleration) was conducted. With the seismic acceleration as a function of distance, the maximum tower height was calculated with various leg splays to model sizing and the possible effect of tip-over (fig. 10.2, left). Rockets landing 10 km away from a tower hub should be sufficient to ensure no adverse interactions.

The S-wave induces vertical acceleration, which limits the theoretical maximum hosted mast payload mass against a deployment with no seismic requirement considerations (fig. 10.2, right). A 10 km keep-out distance is assumed; reducing total mass by 2 percent to 3 percent should negate any possibility for tip-over.

In the next chapter, the concept of lunar infrastructure hubs is expanded to a new commercial service discovered under LunA-10: *Thermal as a service*. Two distinct designs for thermal as a service will be covered.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Sanigepalli, Margulieux, Naclerio, Burrell, Bergman, Zacny, Klein, Clay, Begland, Hubbard, and Glazer are from Honeybee Robotics.
2. Defense Advanced Research Projects Agency (DARPA).
3. See chapter 15 for a more in-depth discussion of the lunar development ages.
4. "10-Year Lunar Architecture (LunA-10) Capability Study," LunA-10 Exploration Announcement Solicitation, August 2023, https://sam.gov/.
5. Ross et al., "Quantifying the Available Solar Power."

11

Thermal as a Service

Edited by Michael Nayak

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11.1 Expanding from a Towered Hub to a Thermal Hub

A large fraction of every lunar payload today is allocated to the thermal system. Radiators, pumps, coolant fluids, pipes, and avionics allow the system to withstand extreme temperatures on the lunar surface. Near the poles, very little solar energy is available due to the local topography that casts long shadows, making power and heat generation a critical demand. Near the equatorial regions, payloads must survive a fourteen-Earth-day night (heat generation) and day (heat rejection). These thermal systems (heat generation and rejection) take up a significant portion of mass of their respective systems:[5] 60 percent for an optical-wavelength power beaming system, 45 percent for an in situ resource utilization (ISRU) plant, 25 percent for surface fission plants; proton exchange membrane fuel cells output up to 45 percent heat.[6] The significant portion of payload mass allocated to thermal management increases development and flight cost, quickly becoming a bottleneck.

This chapter will discuss two designs by which it may be possible to consolidate the thermal management of many lunar users into one system and create a "thermal hub" for payloads with variable thermal demands to interface with. **This creates a new commercial service not heretofore explored before LunA-10: *consolidated thermal-control-as-a-service.*** This service can reduce payload complexity and total mass landed on the Moon. Currently, each user must bring its own custom thermal management system, sized to both radiate its maximum daytime heat load and provide heating to survive the night. Hubs shift the burden of heat management away from the individual users to establish a more efficient local thermal microgrid. This shift is analogous to building tenants on Earth shifting away from individual furnaces and fans to a central HVAC system. This paradigm offers significant mass savings, as discussed in this chapter.

By aggregating numerous users with variable demands, the hub can be designed more efficiently closer to the average demand rather than the sum of peak demands. Further, thermal hubs can recycle waste heat from hot users to heat cold users, reducing electrical power consumption.

11.2 System 1: Modification of the Towered Hub

11.2.1 System Description

A modification of the LunarSaber concept, called Lunar Oasis, is one potential design for a future thermal hub. This is shown in figure 11.1.

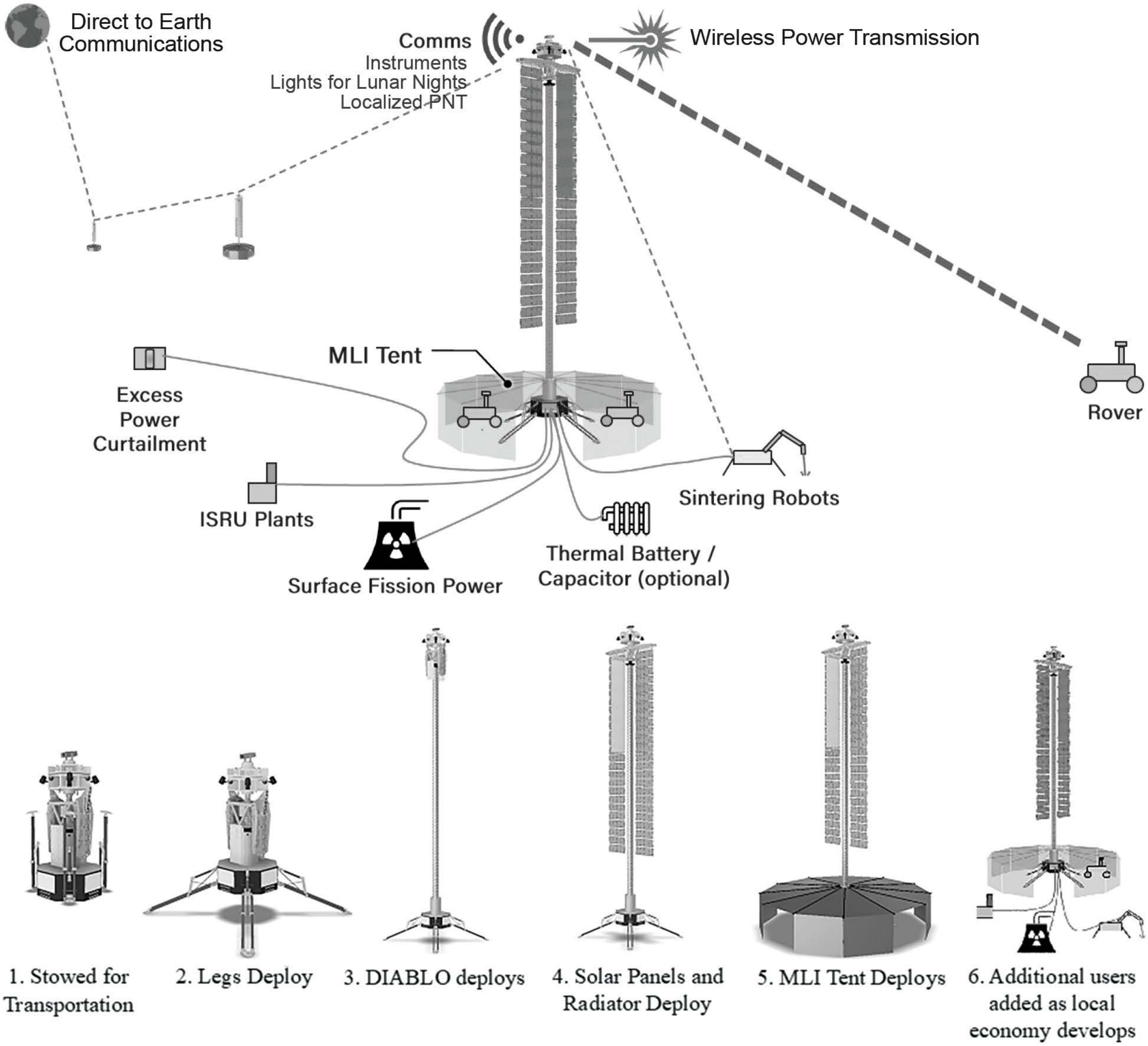

Figure 11.1. (Upper) Lunar Oasis utilizes a LunarSaber tower to create a centralized hub of services for users. (Lower) Lunar Oasis deployment concept of operations. [Credit: Honeybee Robotics]

Specifically, Lunar Oasis consists of the following subsystems:

- Elevated payload platform. Hosts payloads such as power beaming, lights, communications, space traffic management, navigation, and coordination. This is similar to the LunarSaber hub discussed in chapter 10.
- Power. Deployable solar panels that gimbal along the mast axis to point toward the Sun to maximize power output.
- Mast. Deploys DIABLO (Deployable Interlocking Actuated Bands for Linear Operations) to create the mast to raise the payload platform and the power/radiator subsystem.
- Base. Houses redundant avionics and batteries for energy storage and surviving lunar nights. Fluid pumps, valves, and heat exchangers are also located within the base. The an-

chored legs provide additional stability margins for moonquakes and thermal shocks during lunar eclipses.

- Thermal radiator. Radiators are deployed from the masthead, orthogonal to the solar panel that rotates with the solar panels.
- Thermal tent. Near the base, a multilayer insulation (MLI) tent is unfurled from a folded state, significantly reducing variability of the thermal environment for users that reside within the tent during lunar night (e.g., exploration rovers).

11.2.2 Thermal Architecture and Mass Advantages

The primary difference between LunarSaber and Lunar Oasis is the incorporation of a thermal subsystem: pumps, valves, connectors, radiators, and a deployable MLI tent. The Lunar Oasis thermal management system is composed of seven main elements that work together to service users.

- Thermal core. At the center of Lunar Oasis thermal control is a core that actively transports heat between different elements of the system. The core is based on a two-phase pumped fluid loop, consisting of the pump, accumulator, controller, valves, and other components. The two heat loops would serve both low temperature power sources like electronics and high-temperature sources such as fission power and ISRU processes.
- Radiators. Excess heat is radiated to space by large radiators deployed from the Lunar Oasis mast, which rotates to keep the radiators orthogonal to the sun.
- Active users. Heat is actively pumped to and from high-power-density users. Masthead users are directly integrated into the fluid loop prior to launch, while surface users are added post deployment through dust-tolerant fluid connectors.
- Passive users. Mobile or low-power-density users interface with this thermal hub design either through a clamp-on hot plate or radiative heating from the base of Lunar Oasis. These methods allow the users to come in and out of the thermal microgrid as needed, such as a rover that is mobile in daylight but returns to the hub to survive the night.
- MLI tent. A large deployable tent or collection of smaller tents around the base of a thermal hub provides a daytime sunshade and nighttime warmth to mobile or stationary surface users. The tents can be integrated with passive or active thermal connections for additional heating.
- Battery storage. Thermal hubs save excess solar energy in batteries for nighttime heating. Due to the hub's increased solar view time at elevation at the lunar south pole, the longest time that the hub is without solar power is on the order of two Earth days, as opposed to fourteen days at the equator, reducing battery demand.
- (Optional) Radioactive heat source. Thermal hubs can be integrated with a radioactive heater unit (RHU) or fission surface power (FSP) pre- or post deployment. These sources allow the hub to share heat from a single source among all its users, reducing the unit count of these expensive items.

In addition to reduced payload developmental complexity, Lunar Oasis's thermal-control-as-a-service reduces both payload and total flown mass. This reduction is driven by three primary scaling mechanisms that do not require significant TRL advancements to manifest benefits.

1. Consolidation of duty cycles reduces cooling mass by an order of magnitude. Individual payloads that run on a duty cycle, such as laser sintering, power beaming, ISRU, or rovers, must use thermal batteries to reduce peak thermal loads and keep radiator size to a minimum. These must be designed to dissipate the *peak* thermal load, even if their *average* load is much lower. By combining users' thermal needs, the aggregate load can be lower than the sum of individual peaks, assuming users' thermal cycles are not in phase with each other. A simple example is shown in figure 11.2 (left). Shown are thirty lunar users, each with a 1 kilowatt-thermal (kW_t) load, that have a peak-to-average ratio of ten-to-one. A consolidated Lunar Oasis system demonstrates a staggering 80 percent total mass savings compared to an unconsolidated system. This example assumes an uncorrelated average and standard deviation of power demand for each uncoordinated user, but future work will involve detailed microgrid analysis analogous to existing electrical microgrid control.

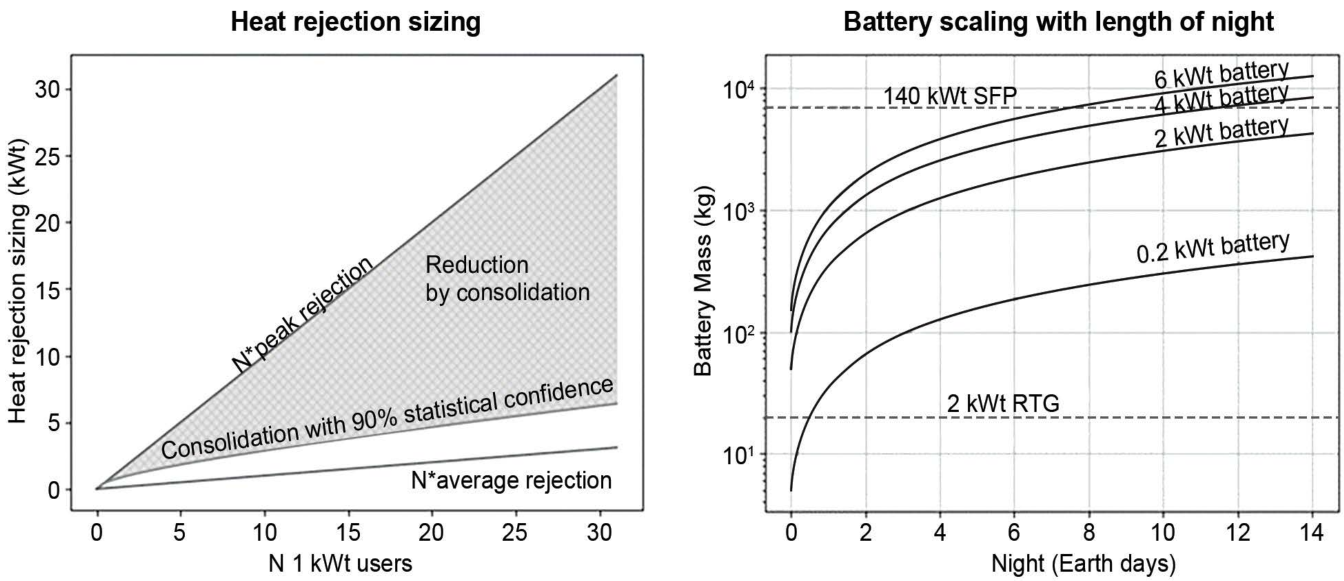

Figure 11.2. (Left) Benefit of consolidation. Plot shown with 1 kW_t users with a ten-to-one peak to average duty cycle. Consolidation line is the expected peak sum with 90 percent confidence using a one-tailed student t-test with a peak of two standard deviations from average. (Right) Battery mass as a function of lunar night length. Masses of surface fission power[7] and a radioisotope thermoelectric generator are shown for comparison. [Credit: Honeybee Robotics]

2. Efficient radiator configuration enables 30 kW scale heat rejection. The height and size of Lunar Oasis enable more efficient radiator configurations than small surface payloads. The double-sided deployable radiators hang from the rotating mass to remain perpendicular to the Sun. Even with a slight view of the hot solar panels, they radiate an estimated heat flux of 630 W/m^2 (watts per square meter) of panel for a double-sided radiator at 40 degrees C, compared to 380 W/m^2 for a horizontal surface radiator. The deployable radiator has virtually no size limit compared to the horizontal radiator, which is limited by the footprint of the surface payload.

3. Thermal energy exchange. Thermal hubs, in general, enable heat sharing, by which waste heat from hot users can be pumped to cold users requiring process heat or nighttime survival. Heat sharing has the potential to significantly reduce the electrical power requirements of the system. Heat pumps can be used to transport heat against the thermal gradient,[8] such as boosting the fluid temperature for ISRU preheating processes.

A surprising insight from LunA-10: **A shared radioactive heat unit reduces battery mass by an order of magnitude at the pole and two orders of magnitude at the equator.** Lunar Oasis can share the heat from a single RHU among all its users, greatly reducing battery mass for nighttime survival (fig. 11.2, right). Thermal consolidation reduces the cost of implementing RHUs by sharing the heat of a single unit with many users.

Several other benefits of a consolidated thermal hub overlap those discussed for hub towers (section 10.2). An elevated platform provides expansive line-of-sight coverage for additional services. It has connectivity to Lunar Oasis's electrical, thermal, and data services, with the capacity to host hundreds of kilograms of payload. A network of Lunar Oases can provide continuous coverage over large areas for communication, surveillance, and navigation services. In addition, the initial mesh network can be situated to provide continual direct-to-Earth communication for users with line-of-sight.

The power benefits of Lunar Oasis are worth a special mention. This innovative thermal hub design serves as a wireless power generation, storage, and distribution node for users on the elevated payload platform and for wired power at the base of the tower. Lunar Oasis will be designed to be augmented with microgrid power generation, storage, and transmission. Wired interfaces will be designed to be compliant with microgrid standards. In addition, Lunar Oasis's thermal capability is synergistic with anticipated microgrid services. Augmented storage and generation such as regenerative fuel cells and radioisotope Stirling generators (RSG) are known to generate significant heat during operations. High-voltage conversion for long-distance wired transmission also requires significant thermal dissipation. Last, hosted power beaming benefits from all three of Lunar Oasis's services: extended LOS from elevation, high-availability solar power, and thermal control as a service for waste heat generated.

11.3 Electrical and Thermal Network Simulations

One of the primary advantages of towered hubs is their increased access to solar power in polar regions. Because Lunar Oasis can provide solar power through the night at its increased elevation, users can now operate through the local night. To survive or thrive through occasional total night, however, thermal hubs would require energy storage.

A synergistic energy storage technology is the regenerative fuel cell, first discussed in section 4.4. Fuel cells store energy in hydrogen and oxygen via electrolysis and supply electricity through water production in a fuel cell. At large scales, this technology has higher specific power than lithium-ion batteries but much lower efficiencies, which makes them impractical on Earth. However, the main driver of nighttime power on the Moon is heating, which makes them well suited for a thermal hub; they can distribute fuel cell electricity for nighttime operations and use waste thermal energy for heating.

Solar power is modeled as a trapezoidal curve with 30 kWe maximum generation, similar to how vertical solar arrays will behave at the lunar south pole. The fuel cell is modeled with the following specifications: 6 kW_e fuel cell discharge rating (48 percent efficiency), 2 kWe electrolysis input rating (85 percent efficient), and 1.6 MWhr (6 GJ) energy storage capacity. The thermal hub charges the fuel cell when its solar power is above 30 percent of its maximum and discharges it whenever power draw from user activity or heating needs exceeds the available solar power. The user electrical demands are generated using notional behavior profiles based on the relative availability (and cost) of electrical power.

Simulation results (fig. 11.3) show some emergent behaviors in the system. First, this simulation demonstrates the value of thermal consolidation. Thermal consolidation maintains user temperatures with less than half of the required radiator area than an individually managed system would require. Second, the fuel cell is demonstrated as the ideal energy storage (fig. 11.4). The fuel cell charges during the day and discharges at total night when solar power is unavailable. With up to 5 kWe from the fuel cell, users can continue low activity through total night. Fuel cell waste heat is sufficient to provide all nighttime heating needs, such that the heaters only turn on at Lunar Oasis morning and evenings, when they can be powered by solar energy.

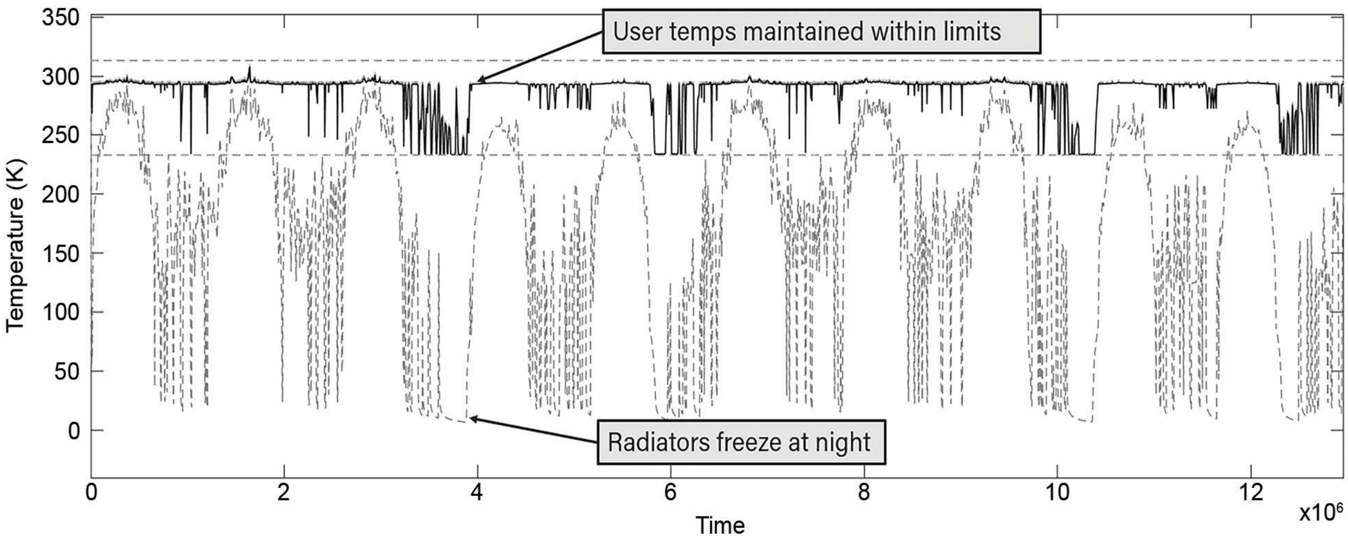

Figure 11.3. Lunar Oasis manages the temperatures of thirty users with consolidated thermal management. Individual management would require 2.1 times more radiator area for the same performance. [Credit: Honeybee Robotics]

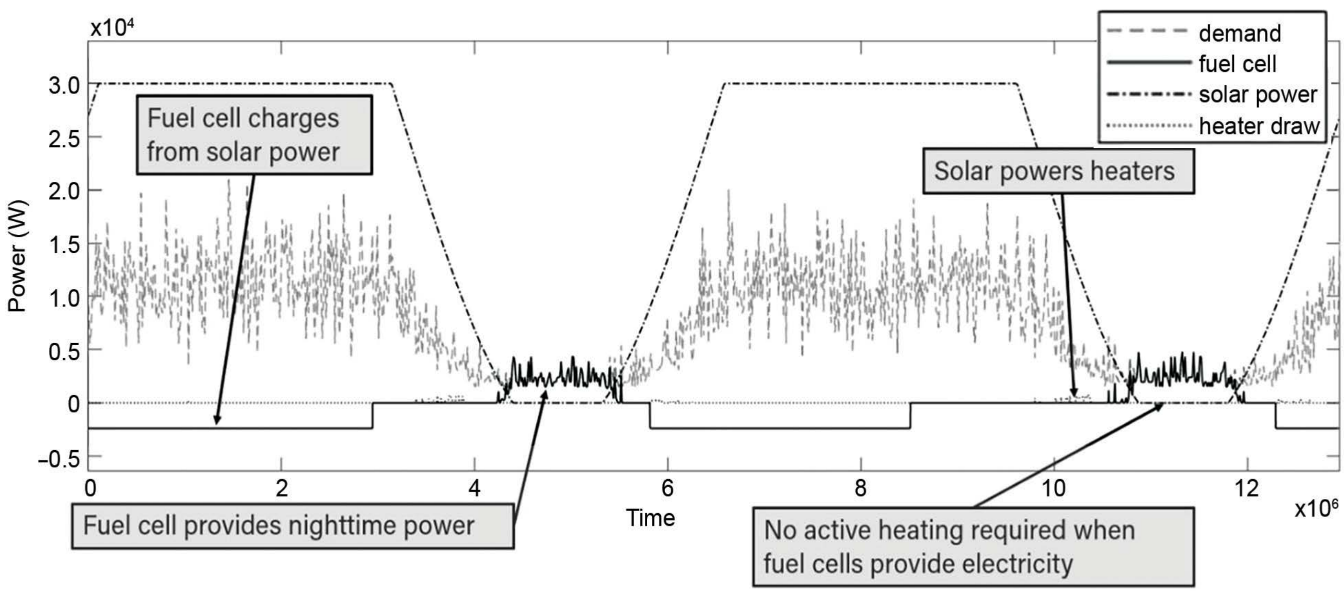

Figure 11.4. Electrical power production and demand of the regenerative fuel cell enhanced Lunar Oasis in a lunar polar region. [Credit: Honeybee Robotics]

11.4 System 2: Laser VMX Material as a Thermal Hub

11.4.1 System Description

Another pioneering approach to thermal as a service leverages the vitreous multi-material transformation (VMX) process discussed in chapter 9 and uses it to create a thermal sink and battery. It also turns lunar regolith into a versatile resource by leveraging its immense potential for energy storage. This innovative approach both maximizes the utilization of available resources on the Moon and paves the way for sustainable energy storage solutions in space.

One of the most promising applications of lunar regolith for energy storage is through the creation of *regolith-based batteries*. These batteries could store energy from intermittent sources like solar power or be directly charged using in situ resources. By converting regolith into a usable form, such as through laser VMX (chapter 9), energy can be stored efficiently, providing a reliable source of thermal energy even during lunar nights.

Laser VMX material is ideally suited to a task of thermal energy storage. Because the material is built up in successive layers, matrix voids for fluid flow, areas of varying grade of VMX for tailored properties, or additives to the matrix (such as the graphene strips discussed in the next paragraph) can all be added during VMX manufacture. The high heat capacity and low thermal conductivity of lunar regolith make it well suited for storing thermal energy over extended periods. During the lunar day, excess energy can be transferred and stored in the regolith. As the lunar night approaches, the stored heat can be gradually released to provide energy to critical systems.

The system concept is as follows. A mass of composite layered VMX material is created via the standard process discussed in chapter 9. An array of conductive material is laid down on top of an intermediate layer of VMX then covered by subsequent layers. A spring material (steel, titanium, etc.) or shape memory alloy is then used to deploy a graphene grid onto the VMX layer, to act as a thermal "connector" for any device that needs to dump thermal energy. The grid and graphene tendrils are connected to the base of a thermal strap, which then connects the thermal battery to the surface or the solar collector. This is illustrated in figure 11.5.

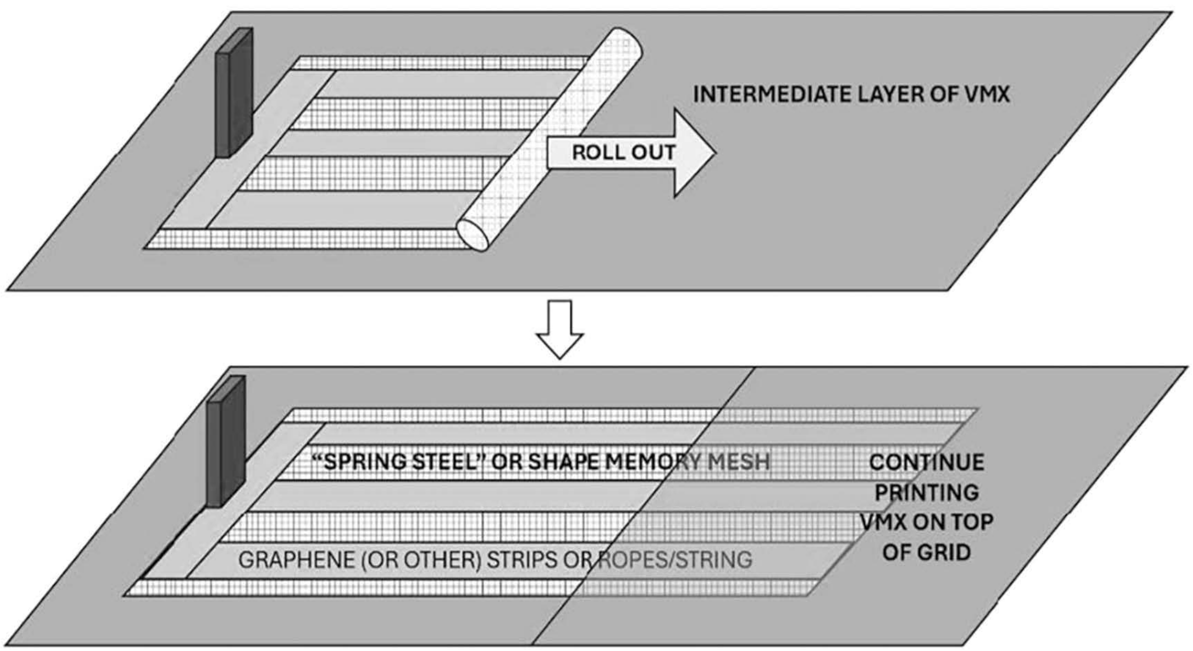

Figure 11.5. Construction details of conductive thermal battery. [Credit: ICON]

11.4.2 Technical Approach

The difference in thermal performance between the various grades of VMX is controlled by two distinct structural effects in the finished material, even if the starting base chemistry is identical. The first structural difference is the porosity of the sintered material; grade 1 has the highest amount of porosity and grade 3 has the least. The second structural difference is relative ratios of crystalline and amorphous phases in the recrystallized material. A grade 3 VMX material has less than 10 percent volume amorphous material in the bulk, while a grade 1 material might be entirely amorphous, due to the lower levels of energy input and relatively rapid quench of the melt pool.

To better understand the effects of crystallinity on the resultant specific heat and density of a material, quench conditions were modeled at 1450°C, 1200°C, and 875°C. These result in fully amorphous, partially amorphous (50 percent), and fully crystalline structures, respectively, to simulate the difference in specific heat and material density that would be anticipated for VMX grades 1, 2, and 3. The different grades of VMX may be contrasted against a granular material with an assumed density of 1.5 g/cm^3 and crystallinity of 50 percent, consistent with the observed densities of uncompacted regolith. For compacted regolith, a theoretical maximum porosity of ~27 percent is observed, putting an upper limit on the amount of porosity one should expect for a lightly sintered material that has been mechanically compacted.

There is a large difference in specific heat capacities between the granular material and the three grades of VMX. While some degradation in battery performance may be experienced when using grade 1 or 2 material, a large delta in the specific heat capacity still exists over the loose lunar regolith.

To simulate the performance of multiple VMX battery concepts, the simulated regolith body, battery, and other subsurface entities were initialized to a uniform temperature of 240 K. The surface of the regolith was set to an initial temperature of 50 K, assumed for all objects extending above the regolith surface (such as the thermal blanket). For other exposed surfaces, such as the top of the thermal blanket, a boundary condition of zero gradient was applied to reflect a state of minimal heat flow across the boundary.

The thermal battery, modeled as a solid block of VMX material, has dimensions of 1 m in length, 0.5 m in width, and 0.2 m in height. This material is sourced in situ and so bears no mass penalty for launch. Surrounding the battery is the regolith region, extending 2 m by 2 m in plan and 0.5 m in depth. The heat source/sink is represented by the tip of a thermal conduit positioned at the edge of the regolith. Power input is specified at either 1,000 W or a constant temperature of 800 K. This condition was maintained throughout the duration of the simulation, spanning fourteen days, to study the transient heat transfer and thermal response of the system under sustained energy input.

Different configurations introduce unique thermal management strategies. Four configurations were explored:

1. A thermal blanket directly atop the VMX battery surface, with dimensions of 1 m by 0.5 m and a thickness of 0.01 m (fig. 11.6).
2. A thin graphene strap of 100 mm width links to a battery buried 0.2 m below the lunar surface.
3. Graphene tendrils cut from graphene sheets employed on a battery embedded 0.2 m below the surface (fig. 11.7).
4. Use elements from the first and third strategy while keeping the battery near the regolith surface.

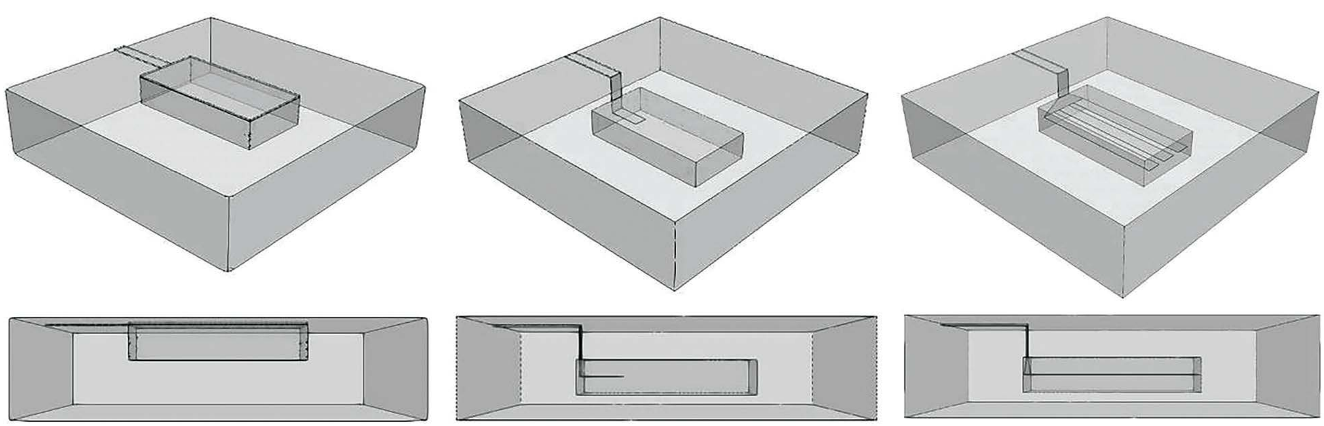

Figure 11.6. System configuration for blanket over exposed VMX mass for heat rejection (left), "monolithic" buried block (center), and block with "tendrils" (right). Not shown is a version of the blanketed mass with tendrils. [Credit: ICON]

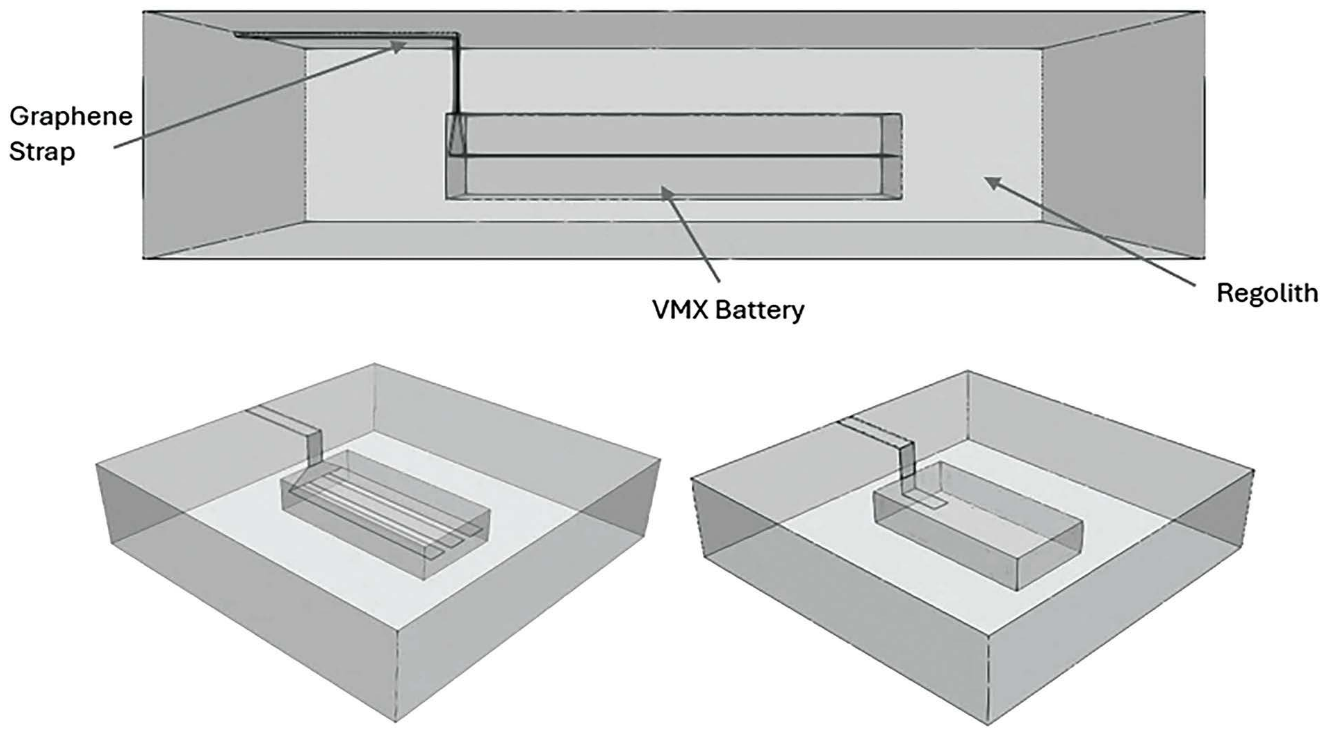

Figure 11.7. System configuration for proposed conductive battery. Graphene was chosen for very high thermal conductivity and space flight applications in the form of thermal straps. The graphene strap to the left provides a "connector" for any device that needs to dump thermal energy. The thermal straps are placed and incorporated into the VMX melt to form a robust conductive interface. The variant shown here on the lower left uses an array of thermal conductor "tendrils" embedded in the VMX battery to enhance bulk thermal conductivity. Bottom right of the image illustrates the device without the added tendrils. [Credit: ICON]

11.4.3 Thermal Simulation Results

A total of ten simulations was performed, consisting of the four geometric configurations (fig. 11.6 and fig. 11.7), at the two power input conditions (1,000 W or 800 K). Further simulations were run to evaluate the impact of using different grades of VMX material.

For the thermal blanket constant power case in figure 11.6, uniform heating of the VMX battery body is seen through the 14-day mark. While some heat is dissipated to the surrounding regolith, especially evident in days 10.5 and 14.0, this is minimal and limited on the exposed sides, as the top surface is protected by the single-sided blanket. Results are shown in figure 11.8.

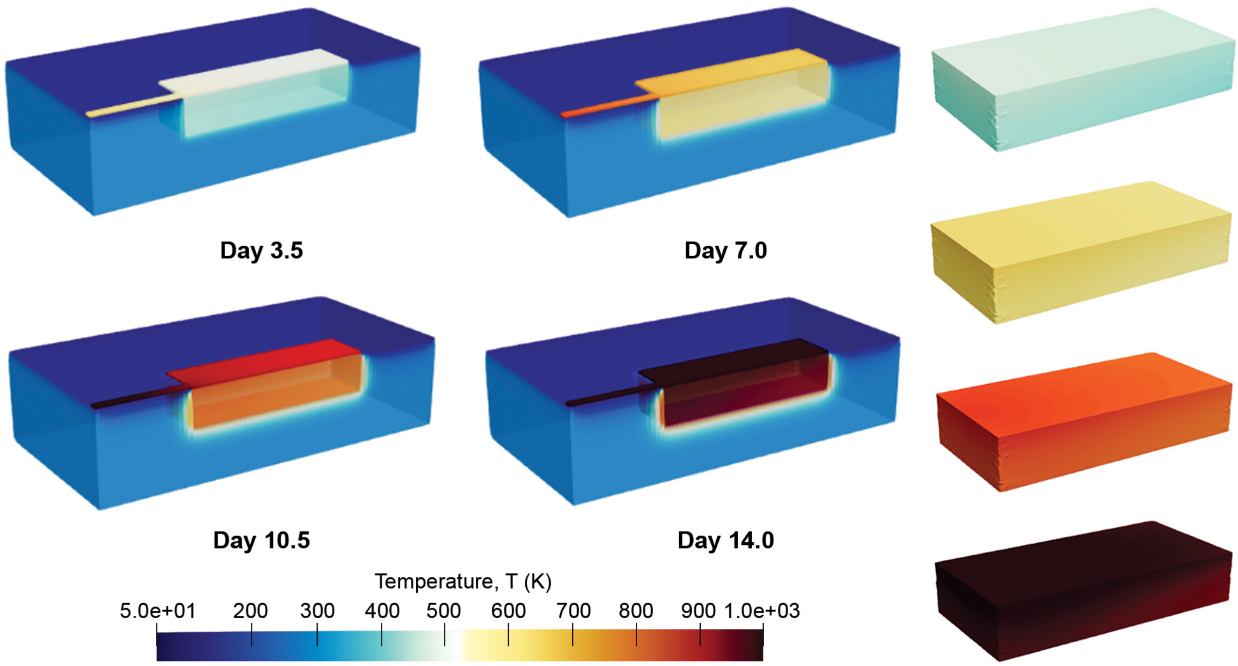

Figure 11.8. Thermal blanket configuration under constant 200 W input power condition. Color contour plot shown of surface temperatures; physical body is section cut. [Credit: ICON]

This result contrasts with that of the single graphene strap case, also under constant input power. Here, the thermal distribution over time follows the path of the strap itself; initially heating the strap and proximate VMX in days 0–3.5, followed by additional VMX heating up to day 7.0. Through day 10.5, all of the VMX battery has been non-uniformly heated past 500 K. By day 14.0, the system ends with an exceptionally hot region near the strap and much cooler section at the end of the battery. Significant heat also bleeds into the surrounding regolith near the hottest parts of the battery, and from all sides. Results are shown in figure 11.9.

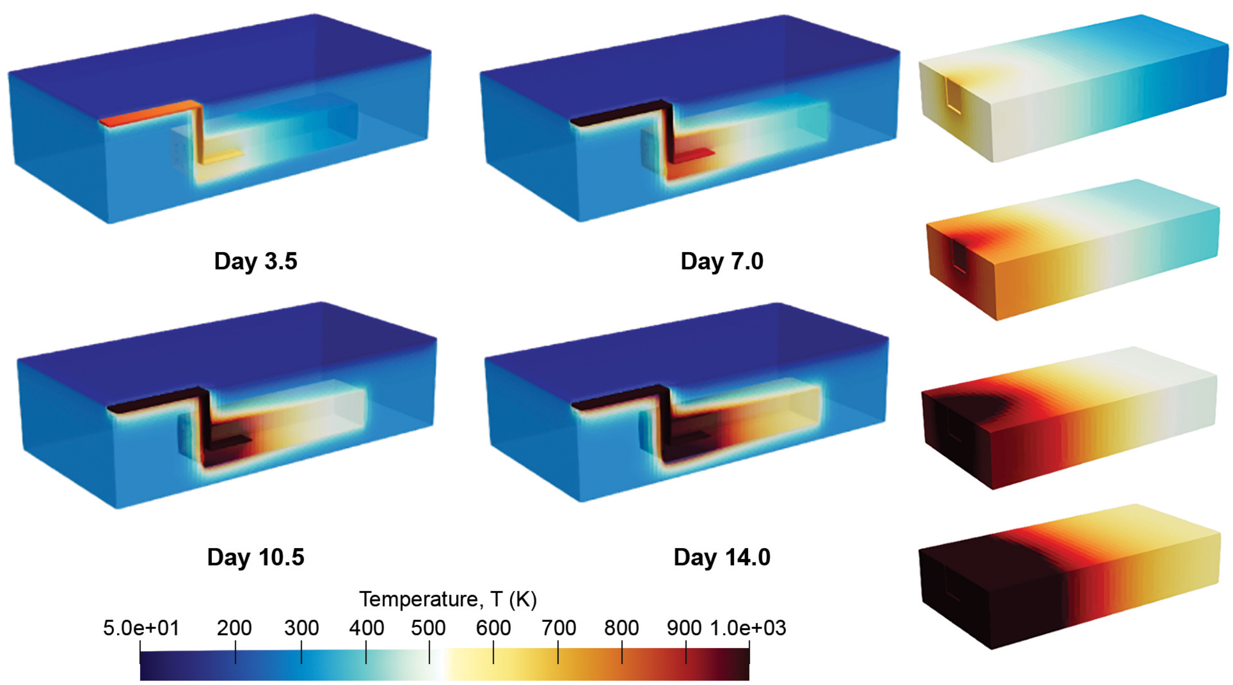

Figure 11.9. Graphene strap configuration under constant 200 W input power condition. [Credit: ICON]

In the third configuration, uniformity in heating was reintroduced. Like the other graphene configuration, thermal energy largely trailed the path of the strap and tendrils. With a greater volume of graphene, heat was better distributed and the VMX battery heated similarly to the thermal blanket configuration. Unlike the thermal blanket, the buried battery resulted in more surfaces exposed to the cold regolith and thus more area to conduct heat. Results are shown in figure 11.10.

For all simulations, the energy input into the setup, energy stored in the battery, and storage efficiency were calculated. Results for constant temperature cases, constant power, and differing VMX grades are summarized in table 11.1.

The storage efficiencies of all configurations remained consistent between the constant temperature and constant power conditions. This congruence boosts confidence in the robustness of the thermal models. The thermal blanket and graphene tendril configurations, in particular, were highlighted for their efficiency in optimizing energy storage and dissipation.

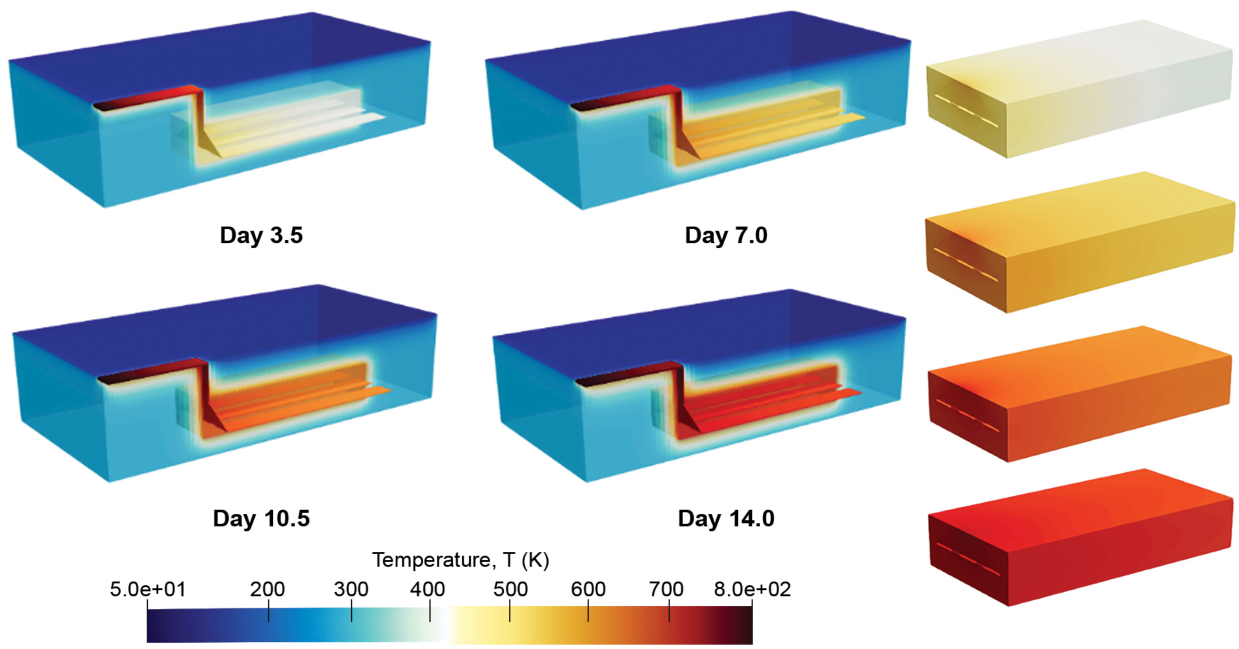

Figure 11.10. Graphene tendrils configuration under constant 800 K input temperature condition. [Credit: ICON]

Table 11.1. Simulation results

Comparisons for battery configurations with 800 K input (constant temperature)				
Measured Values	*Thermal Blanket*	*Graphene Strap*	*Blanket + Tendril*	*Graphene Tendril*
Input energy [kW_t·hr]	48.0	38.0	74.4	99.1
Energy stored [kW_t hr]	36.7	27.0	37.2	30.6
Comparisons for battery configurations with 200 W input (constant power)				
Measured Values	*Thermal Blanket*	*Graphene Strap*	*Blanket + Tendril*	*Graphene Tendril*
Input energy [kW_t·hr]	67.2	67.6	67.2	67.2
Energy stored [kW_t hr]	50.7	47.9	31.6	20.0

Comparisons for battery configurations with 800 K input (constant temperature)				
Measured Values	*Thermal Blanket*	*Graphene Strap*	*Blanket + Tendril*	*Graphene Tendril*

Comparisons for VMX grades with 800 K input (by VMX grade)			
Measured Values	*Grade 1 Graphene Strap*	*Grade 2 Graphene Strap*	*Grade 3 Graphene Strap*
Final strap temp. [K]	778	778	779
Final battery temp. [K]	637	639	643
Input energy [kW_t hr]	38.9	38.6	38.0
Energy stored [kW_t hr]	27.0	27.1	27.3

11.5 Summary and Conclusion

By introducing practical and scalable thermal consolidation, Lunar Oasis and the VMX regolith battery disrupt the traditionally envisioned lunar system architecture.

Consolidation enables multiple paradigm shifts in lunar thermal design:

- Combining multiple users' disparate duty cycles reduces the peak thermal dissipation needs of the combined system.
- Consolidating dissipation allows for more complex and more efficient radiator configurations.
- Consolidation enables the trading of thermal energy, reducing power requirements for process heat applications and reducing storage requirements for survive-the-night applications.
- A single radioisotope system can be shared by multiple users for heat generation.

These technologies, if fielded, will quickly become critical infrastructure hubs for the emerging lunar economy. Now users can leverage these services to significantly reduce their mass and cost to get to the surface and see their developments simplified and de-risked.

Users on the elevated platform of a towered thermal hub also enjoy extended areas of coverage, reducing unit count and operating costs. Inside Lunar Oasis's insulative tent, users experience significantly reduced environmental variability, simplifying their design and operation while benefiting from thermal consolidation services. Both LunarSaber and Lunar Oasis can be tailored to polar, mid-latitude, and equatorial regions of the Moon.

The pioneering approach of vitreous multi-material transformation material as a thermal sink and battery exploits native characteristics of the lunar regolith for infrastructure construction operations at zero added launch-mass penalty. This research thrust could revolutionize the thermal regulation and energy storage systems for lunar missions, enhancing their reliability and sustainability for ongoing and future endeavors.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Sanigepalli, Margulieux, Naclerio, Burrell, Bergman, Zacny, Klein, Clay, Beglund, Hubbard, and Glazer are from Honeybee Robotics.
2. Authors Jensen, Koube, and Hayes are from ICON Technology Inc.
3. North Fracture Group.
4. Defense Advanced Research Projects Agency (DARPA).
5. Nayak, "Six Hypotheses to Accelerate a Lunar Economy."
6. Saman et al., "Thermal Management of Electrochemical Energy Conversion."
7. Olsen, et al., "Deployable 40 kWe Lunar Fission Surface Power Concept."
8. Van Gerner, et al., "Heat Pump for Space Applications."

12

A Rail Network for Lunar Logistics

Edited by Michael Nayak

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12.1 Introduction and Framing

Efficient logistics and transportation of resources are essential to sustaining a broader multiservice commercial infrastructure framework. A mining site without a means to transport the mined minerals efficiently to processing facilities will not result in refined materials sold to customers. On Earth, resources are distributed through mobility infrastructure solutions including air, ground, and sea vehicles; pipelines; electrical grids; fiber optic and coaxial lines; and wireless transmission points. These resource distribution channels require a physical infrastructure presence in the form of distributed nodes or sites, such as substations, towers, or distribution plants. Many rely on a continuous network of physical connectivity such as roads, pipelines, and rail networks.

This chapter explores the construction and operation of a rail-based physical network on the Moon. To frame the lunar rail and its place in the lunar economy, one must first frame SpaceX's Starship and its potential to upend the existing paradigm for mass to the Moon.

The Starship-Super Heavy launch system is a 121 meter (m) tall, 9 m diameter vehicle consisting of a Super Heavy first stage combined with a Starship second stage. Starship is expected to provide full and rapid reusability, planetary landing capability, high-cadence aircraft-like operations, and super heavy class payloads (~50 to 100 tons). Starship can serve as an enabling element of a lunar base by providing economical cargo delivery at unprecedented scale. Several variants of Starship are planned for mission-specific tasks, including a tanker variant for delivery of propellant to low Earth orbit (LEO) and return, a depot variant for storage and transfer of propellant on orbit, and a lander variant for crewed and cargo missions to the Moon.[5]

One hundred tons of cargo delivery to the surface of the Moon, in one shot, will change the face of lunar logistics. Experience from large-tonnage deployments to military forward operating bases shows the informed observer that large-volume shipments tend to "sit in place" until something urgent at the bottom of the pallet is needed. SpaceX's responsibility ends once cargo is safely offloaded from the Starship, but for commercial companies, time is revenue. The lunar economy cannot waste time with a large tonnage of lunar cargo simply sitting in a pile. A single lunar terrain vehicle (LTV)-class rover can carry ~1,500 kg of cargo at speeds of 10 to 20 km/hour. At this rate, it will take a single LTV 133 trips, and thousands of hours, to unload a single Starship and move equipment from point of delivery to the point of need.

And this is just one Starship.

Given a growing lunar presence, mobility across spatially separated sites becomes a key service. Challenges with rover-based transportation systems to broadly support the expansion of lunar surface commercial operations include range, payload capacity, transport speed, rolling resistance, surface wear, dust generation, and overall recurring cost of maintenance. To unload and locally transport goods from a Starship with LTV rovers would be equivalent to terrestrial commercial freight hauling with all-terrain vehicles. Overall, the concept of a core rail transportation network can act as the spine on which lunar civilization can be built and multiple site destinations connected.

This chapter explores the economic and engineering basis for a Lunar Rail Network Infrastructure to meet this need, today unanticipated. Conceptual design and analysis of construction and maintenance equipment, rail route infrastructure, integrated rail vehicles, rail station infrastructure, system interfaces, and a system scaling plan are covered. The network begins with minimum viable experiment (MVE) phases, expanding into a pilot rail network and eventually a full-scale operational network.

Rail systems in early America greatly accelerated commercial growth and westward expansion before the automobile. Being more efficient than long-haul trucking, they are still the preferred choice of moving large quantities of resources by land.

To increase commercial viability, LunA-10 drove every concept toward being capable of supporting a variety of commercial services. In this vein, the lunar railway, as presented in this chapter, is more than just a transportation and logistics enabler. Lunar rail corridors can also support (1) routing of pipelines for fluids and gas transport, (2) integration of thermal management solutions, (3) integration of wired power and data lines, and (4) installation of towers to support communications, positioning, navigation, and timing (Comms/PNT), solar power collection, and wireless power transmission. The incorporation of other infrastructure services reduces the amortized cost of infrastructure for each service alone.

Creating physical infrastructure requires significant geotechnical engineering and soil construction operations for stability and longevity. Initially, the largest constraint will be availability of energy and the mass of construction equipment that can physically be brought from Earth. By creating a multiservice Lunar Rail Network, fewer physical corridors and sites will need to be developed, minimizing the cost of creating an infrastructure for a sustainable and scalable human lunar presence.

The Lunar Rail Network Infrastructure study performed a deep dive into systems engineering, business analysis, and concept design engineering to consider viable solutions for bringing the benefits of rail transportation to the lunar surface within ten years. Earth-based starting points were analyzed for their application to the unique challenges of the lunar environment.

For all analysis in this chapter, the lunar rail is assumed to be located at the south pole, an extreme construction environment expected to have a high density of human and robotic lunar activity.

12.2 Lunar Rail Network: Overview of Services

The primary service of the Lunar Rail Network is movement of freight, including raw materials (e.g., regolith), processed goods (e.g., oxygen, foundry products such as beams and rail segments), and equipment (e.g., rovers, in situ resource utilization [ISRU] machines, towered and thermal hubs, and scientific payloads).

In addition to tanker or cargo railcars, material may also be transported via a buried adjacent or co-designed "pipeline." Power can be distributed to bases and settlements using wired transmission through the Lunar Rail Network stations, with easy access for inspection, maintenance, and modification. Communications can be transmitted reliably with wired fiber optic connections embedded into the network. With the drastic range of lunar temperatures, heat management will be vital. The wide reach of the Lunar Rail Network permits heat to be rejected into the system and distributed to where it is needed or radiated to space by leveraging large lengths of available area. Individual systems may simply plug into the infrastructure and utilize the aforementioned services.

The Lunar Rail Network includes four primary system areas: (1) construction and maintenance equipment, (2) rail route infrastructure, (3) rail station infrastructure, and (4) integrated rail vehicles. Each primary system area includes subsystems and sub-products, shown in figure 12.1.

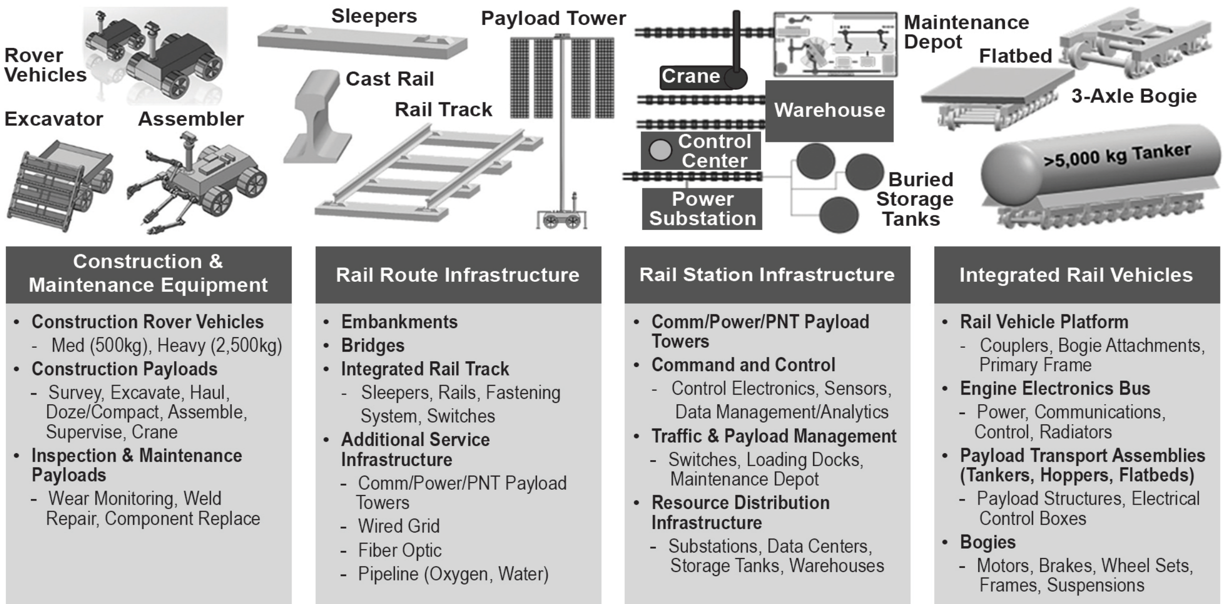


Figure 12.1. Lunar Rail Network Infrastructure product data structure. [Credit: Northrop Grumman]

12.3 Lunar Environmental Design Considerations

The operating temperature range for the rail system can vary from 50 K to 301 K.[6] Lunar night is topography-dependent at the south pole. At just 2 m above the surface and filtering out relatively short and survivable durations of lunar night, various locations near Shackleton crater have continuous illumination periods over six months.[7] Greater elevation and greater ability to survive short-duration lunar night, especially with cryo-operable and cryo-tolerant electronics, can simplify designs.

Radiation effects imparted by the solar wind, solar energetic particle events,[8] and ultraviolet/extreme ultraviolet radiation must be considered when designing the rail's electrical components. Significant dust deposition could cause reductions in wheel, rail, sensor, and electronic efficiency. During the construction phase of lunar rail build up, there will be a requirement for sensors, which will be susceptible to dust. Pitting and abrasions may degrade the surface friction of the rail over time. Nanophase iron may be magnetic in nature and adhere to the rail, altering surface properties. Fueling seals or flanges may be damaged or degraded. Particles smaller than 10 micrometers can enter electronic systems within the rail network. Electrical shorting due to the charged nature of the lunar dust must be considered. The low gravity environment increases the likelihood that particles may deposit in electronics and mechanically sensitive areas. Therefore, each rail subsystem must be designed with barriers to prevent the buildup of dust.

A metal rail may be capable of rejecting dust electromagnetically from its surface, particularly if the system is also used as a power or thermal conductor. This system creates an electric field that ripples outwards to "shake" lunar dust off the rail with a 99 percent efficiency. An estimated 200 V AC power would be required on the Moon, which differs from high-voltage DC power that longer distance power transmission will likely utilize. This technique is one of the leading rail solutions applicable to flat surfaces such as solar panels, radiators, sensors, mechanisms, and robotic joints. Solid lubricants may be required to prevent cold welding and dust adhesion.

Deep and even shallow moonquakes reverberate and persist for a much longer time than their Earth equivalents. Lunar seismic signals have low attenuation and high scattering, enabling them to persist for hours (longer than four hours in some cases).[9] This characteristic of the Moon is due to its lack of water, which dampens seismic waves, and a heterogeneous outer shell composed of "fractured" lunar regolith structures churned up from impacts or composed of brittle, underground lava tube networks.[10] Thus, even moonquakes of a smaller magnitude may cause smaller but more sustained damage to rail structures. To prepare for the worst case, the rail should be designed to withstand moonquakes of body-wave magnitudes of up to 6.0 on the Richter scale for 100+ minute periods of time.

Key constraints in using ISRU metals for lunar rail construction are the limited alloy availability and challenges with alloy extraction and purification. Elements not available via ISRU must be shipped from Earth at a significant cost. Thus, the design space is constrained to readily available ISRU materials and alloys (detailed in chapter 6). Of the primary structural metals available on the Moon, aluminum (Al), iron (Fe), and titanium (Ti) offer a range of alloys and properties. A detailed study into each, as well as key alloying elements, was undertaken.

Ti alloys offer excellent mechanical performance and high hardness but are limited in abundance at the lunar south pole. Similarly, limited Fe content in polar regolith may increase the cost and challenge of extracting sufficient raw iron for rail manufacturing. Conventional rail steels have a ductile-to-brittle transition temperature in the range of -20°C to -60°C, resulting in a dramatic decrease in fracture toughness. Austenitic stainless-steel alloys would require substantial imports of nickel and chromium from Earth.

Al is the most plentiful at the south pole, as are many of its key alloying elements, making it a convenient choice for an ISRU-produced lunar rail. The mechanical performance of most Al alloys is stable even at cryogenic temperatures. Thermally stable alloys include Al-4032, sometimes used in engine pistons, and Al-6061; both are heat-treatable but retain their strength in warm environments.[11] Other alloys such as Al-5083 leverage alternate strengthening mechanisms such as solution strengthening, cell strengthening, or cold working. Top-performing heat-treated aerospace aluminum alloys such as Al-7075 may be susceptible to over-aging and significant softening after months in direct solar illumination.

Some Fe, Al, and Ti alloy compositions are suitable for the lunar environment. For Fe, austenitic steels are best able to handle cryogenic temperatures. For Al, 4xxx, 5xxx, and 6xxx series alloys (such as 4032, 5083, 6061, and AlSi10Mg) are competitively strong, leverage elements in the local regolith, and can handle temperature extremes. As the lunar economy expands, Ti-rich basalt regolith may enable the incorporation of ISRU titanium parts.

Wear and cold-welding effects are a concern in vacuum,[12] due to the combination of fretting (the most severe type of wear) and a vacuum environment (which dramatically accelerates wear). On Earth, native surface oxides (typically 1–8 nanometers thick) can improve wear resistance and reduce cold-welding risks, as the thin oxide barrier protects both surfaces and prevents metal-metal atomic contact. In the Moon's vacuum environment, any wear will quickly break through the native oxide layer. One thorough study compares several aerospace alloys and their associated cold welding/adhesion characteristics in static, impact, and fretting conditions in a vacuum.[13] Fretting/sliding/vibrating (most relevant for a lunar rail) shows the worst cold-welding effects, and the highest adhesion forces are ten to thirty times higher than impact adhesion forces. Without the protective native oxide, when the two metal surfaces make contact, they can adhere to one another and upon separation tear away chunks of material from the other surface, thus dramatically accelerating the wear process.

Using dissimilar metals can reduce cold welding and wear damage. Having two separate hardness values can influence relative wear (as the softer surface will wear preferentially). Thus, by encircling the wheel with a thin, removable, softer metal tire or rim, the rim could wear preferentially (preserving and elongating the rail's life) and could be easily replaced at regularly scheduled maintenance intervals. A detailed analysis of rail and wheel materials selection options concluded that there were two promising approaches for further investigation: (1) hardening the aluminum alloy rail surface and lubricating the titanium alloy wheel surface, known as duplex treatment, or (2) utilizing a highly hydrogenated diamond-like coating on both surfaces.[14] A continuously applied graphite solid lubricant solution might provide some relief if dust abrasion can be prevented, but testing is required to determine viability of this potentially simplistic approach.

To reduce risk and improve the capabilities of the lunar environment, research into reliable ISRU extraction of dominant elements and identifying the minimum concentration for reliable extraction is desired. If new approaches and technologies enable trace elemental extraction, the alloy design space could be dramatically increased. **There is a tremendous opportunity to develop and further optimize foundation alloys, coatings, and lubrication methods that are well suited to the expansion and development of the lunar frontier**.

12.4 Lunar Rail Architecture Concept

12.4.1 Construction Vehicles

To meet the demands of rail construction, six vehicles were designed under LunA-10; these are summarized in figure 12.2.

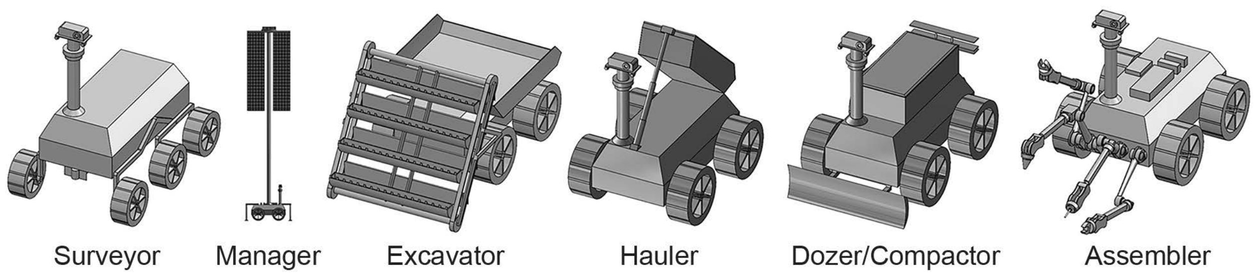


Figure 12.2. Concept designs for six track-laying vehicles required. [Credit: Northrop Grumman]

Surveyor. The Surveyor is similar to heritage rovers designed for science and exploration. This vehicle surveys areas to refine non-local observations and check intended routes for unforeseen challenges that may require special construction or rerouting. At a minimum, the Surveyor hosts a ground-penetrating radar to detect unmovable rocks that interfere with the planned route and a penetrometer to characterize the regolith that will be encountered by other construction vehicles. **Both instruments also contribute to scientific discovery as new areas are explored**. Additional instrumentation such as spectrometers can increase scientific return or perform surveying for ISRU resource reserves.

Manager. Once the Surveyor has checked routes for safety, the Managers drive to areas surrounding the intended rail route but out of the way of the construction to deploy comms/PNT outriggers and towered hubs (discussed in chapter 7 and chapter 10). The Managers provide: (1) improved communication sight lines, (2) improved PNT, (3) external observation of construction for telemetry and verification, and (4) offloading sensitive components from many vehicles in a harsh construction environment to a vehicle experiencing less dust and vibration.

After the Managers are in place, the construction effort really begins.

Excavator. The lunar surface is covered in a layer of fluffy loose regolith, which may be of greater depth at the south pole than elsewhere on the lunar surface.[15] The excavator uses a bucket ladder ahead and at least as wide as the vehicle to clear away this fluff. By using many shallow cuts, the vehicle mass and power can be reduced. While NASA is largely pursuing bucket-drum excavators (e.g., RASSOR and IPEx), available reading suggests the bucket ladder excavating implement is the most productive and energy efficient and is the most successful implement in NASA's Lunabotics Challenge.[16] Because the bucket ladder is ahead of the vehicle, the excavator has a bin to collect the regolith for a duration, eliminating the need for a following vehicle. Particle size distributions from previous lunar landings indicate a low gravel (particles >~2 mm) content, but similar information is not currently available for the south pole.[17] If there is a significant gravel content or even just very dense regions of regolith, a "ripper" tool on the excavator could significantly reduce the required excavation energy.[18] The ripper could be implemented as claws along the buckets, on the bucket chain, or as a separate rake-like design.

Hauler. When the excavator's bin is full of excavated regolith, it is dumped into the bin of a hauler, such that the excavator downtime is relatively short. The bin is closable to avoid dust generation and provide volatile protection while hauling. The hauler then transports the regolith away, likely directly to a nearby ISRU station. From there, the regolith can be processed to extract valuable resources and produce goods. **The hauler therefore enables an ISRU value chain,[19] creates a monetizable delivery service to buy down costs of rail construction, and incentivizes the location of ISRU foundries adjacent to rail construction areas**. Regolith may also be brought to areas that require fill work or complete fill work with waste regolith instead.[20]

Dozer/Compactor. The dozer/compactor combines a few key tasks into one shared vehicle that requires sufficient weight for traction and compaction. Even though the regolith below the fluff layer is denser, the excavation will likely disturb this denser regolith, creating new fluff. Once the route is cleared, the dozer/compactor compresses the foundation for the track to ensure it can support expected loads. Vibration will improve compaction performance for lunar regolith. The dozer/compactor has an underbody vibratory plate implement for quicker, surface-level compaction as well as a rear-end vibratory pin and plate compacting implement for deeper regolith. Moving large amounts of regolith is necessary as more railway is built. Non-optimal routes from a construction perspective may be necessary. A dozing blade helps accomplish this task. It can be used for both coarse and fine grading and requires sufficient vehicle weight to maintain traction while pushing. The dozer/compactor also has a coverable bin that can be filled with regolith, similar to the hauler, to allow for a greater compacting/traction force.

Assembler. Once the route has been cleared and the foundation prepared, the assembler uses its multiple robotic arms to place sleepers, sleeper pads, rail segments, and other track components and then join them together. Two arms place larger objects, while another two arms join pieces via laser-based sintering, welding, or clip installation. Once enough rail is initially built, the assembler can continue building while a railcar delivers components to the assembly site. With add-ons such as a bed or spool holder, it also supports additional service initiation along the route, including laying cable, connecting interfaces, and maintenance.

12.4.2 Integrated Rail Track

The integrated rail track must be constructed from scalable, repairable, and replaceable components and is composed of four components (fig. 12.3, left). Starting from the lunar surface is the *sleeper*, a sintered regolith form that distributes the loads of the rail line. Next is the *sleeper pad fitting*, embedded into the sleeper during fabrication. The pad fitting is a metal structure providing increased flexural strength and greater support to the rail forces as they translate into the sleeper. The pad fitting connects to the clips, which hold down the rail. The clips act as a sacrificial piece for the pad fittings and sleeper, designed to break under excess rail loads before the forces translate down further. The clips are a spring loaded, flexible connection, allowing the rail to slide with thermal expansion and contraction. One pad per rail segment may need to be welded to the rail to facilitate reaction of braking and traction loads.

A major consideration in the design of the rail track is the large temperature swing between day and night cycles. Thermal expansion is relative to the length of the rail. Therefore, the rail is designed in short segments, with joints to flexibly bridge the neighboring segments. The rail segment length chosen is 2 m, which will experience a 15 mm length change due to thermal expansion and contraction. Vertical deflection continuity is ensured by mounting the end and start of adjacent rail segment pieces to the same sleeper.

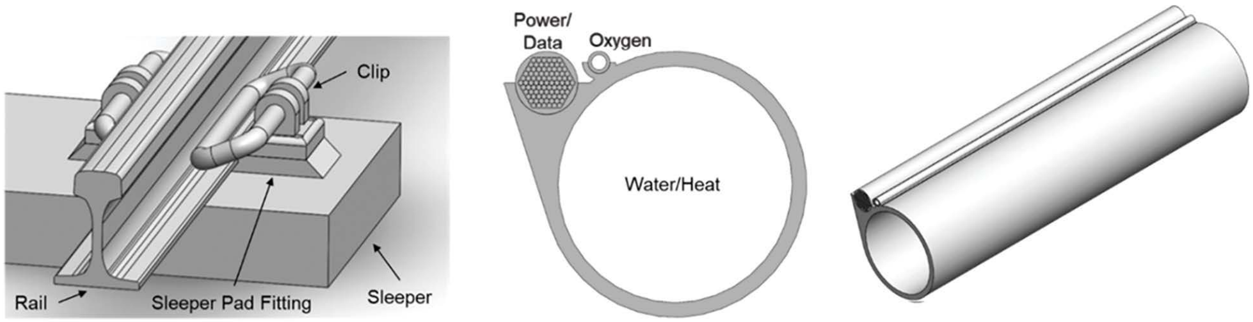


Figure 12.3. (Left) The integrated rail design, and its four main components. (Middle and right) Additional service infrastructure including power/data wired transmission, a water/heat pipeline, and an oxygen pipeline. [Credit: Northrop Grumman]

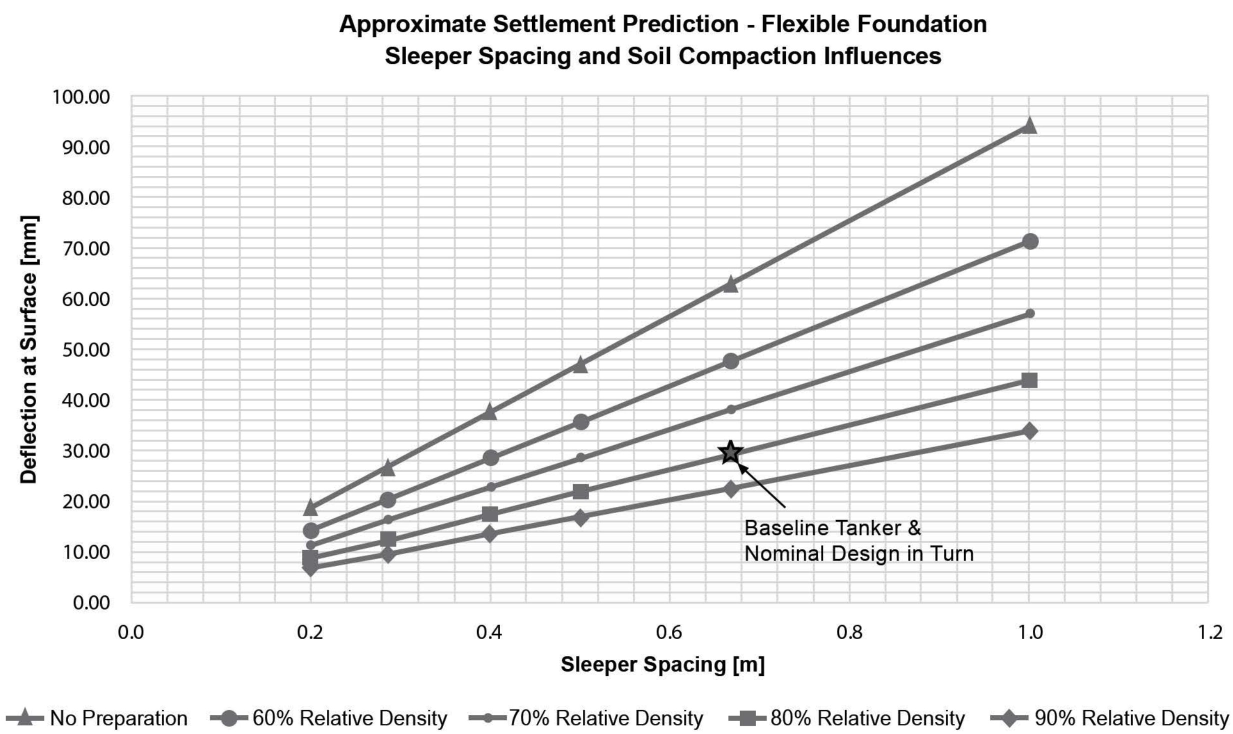
Any proposed region of service on the Moon likely includes some elevation changes. For discrete embankments and columned bridges, integrating the bridge platform into the grounded rail line is a critical design step not explored in this study. The spacing of columns and discrete embankments needs to be designed such that rail loads are properly displaced and segments remain joined evenly despite thermal effects.

Potential additional services provided along the rail line include a power/data wired transmission, a liquid water/heat pipeline, and a gaseous oxygen pipeline (fig. 12.3, middle and right). Power can be transmitted via high-voltage DC cable from a central power source to facilitate a nearly 2 MW demand. A larger cable is used for near transmission (less than 10 km), while a smaller cable is used for farther transmission. Data could be transmitted at up to 169 gigabytes per second (Gbps) along the first 10 km and 61 Gbps beyond via fiber optics. The water/heat pipeline will transfer away the heat dissipated by the power cable and distribute it to thermal customers. Initial analysis indicates the potential for 2 MW heat transfer over 30 km with just 10 K temperature difference between source and sink. The water may also be used in support of ISRU or biological needs. The oxygen pipeline can support human consumption or propellant transport, although tanker railcars may make more sense for large quantities. These additional service pipelines are buried to reach a more stable temperature than on the surface.

A major focus during rail network design was the geotechnical engineering of the foundation and compaction requirements of the lunar soil subgrade for supporting rail loading. Finite-element analysis, static geotechnical analysis,[21] and the study of potential shear wave influences on the dynamic operation of trains were conducted. Under LunA-10, it was found that the settlement for general static loading in straight sections, even with minimal compaction, is less than 1 cm for the loading of 600 to 900 kg/axle. Dynamic amplification and expected additional loading under maximum velocity in a sloped, minimum radius turn suggests that 80 percent to 90 percent relative density (Dr) compaction will be needed in some sections to maintain elastic settlement below 3 cm. Increasing the number of sleepers in turning track reduces construction energy and time compared to the additional compaction burden.

Figure 12.4 (top) shows the results of this analysis. It provides a general understanding of settlement, for various rail car loadings at 80 percent Dr, and sleeper spacing influences under different levels of soil compaction for nominal loading. The "baseline tanker" for this analysis is a fully loaded 10,000 kg carrier. Train speeds of 30–60 km per hour remain under the anticipated lowest shear wave speed for the lunar soil, which means the deflection in the soil is pseudo-static for this design. Therefore, a dynamic model to consider rail carrier suspension dynamics and analysis of dynamic interactions due to track irregularities from wear, inconsistent settling, and thermal expansion were not conducted. Instead, a factor of 1.5 was applied to the maximum pseudo-static load in figure 12.4 to account for unmodeled behavior.

Cyclic strain levels in the soil were on the order of 0.01 percent to 0.02 percent, near the threshold strain for Earth soils. Thus, at the highest speeds, there could be additional nonuniform settling compaction under many load cycles. This may necessitate foundation maintenance. Additional studies are necessary to better understand the longevity of the geotechnical design under the nominal mass loading and train dynamics.



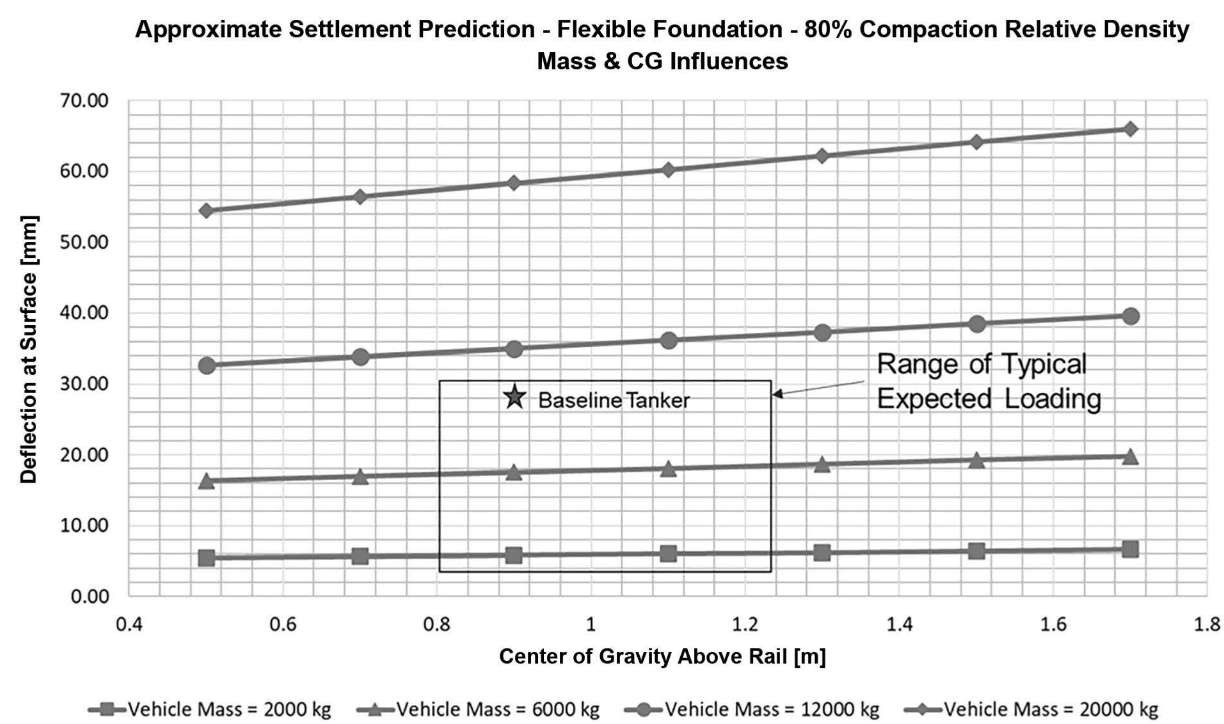


Figure 12.4. Geotechnical analysis summary plots for peak dynamic loading. [Credit: Northrop Grumman]

12.4.3 Integrated Rail Vehicles

The integrated rail vehicle design is largely inspired by terrestrial rail systems, with adaptations for lunar functionality. The foundation is a standard bogie assembly, a frame, and interchangeable carriers. A basic rail line train consists of one engine, one tanker, and two of each of the basic carriers: *flatbed* and *hopper*.

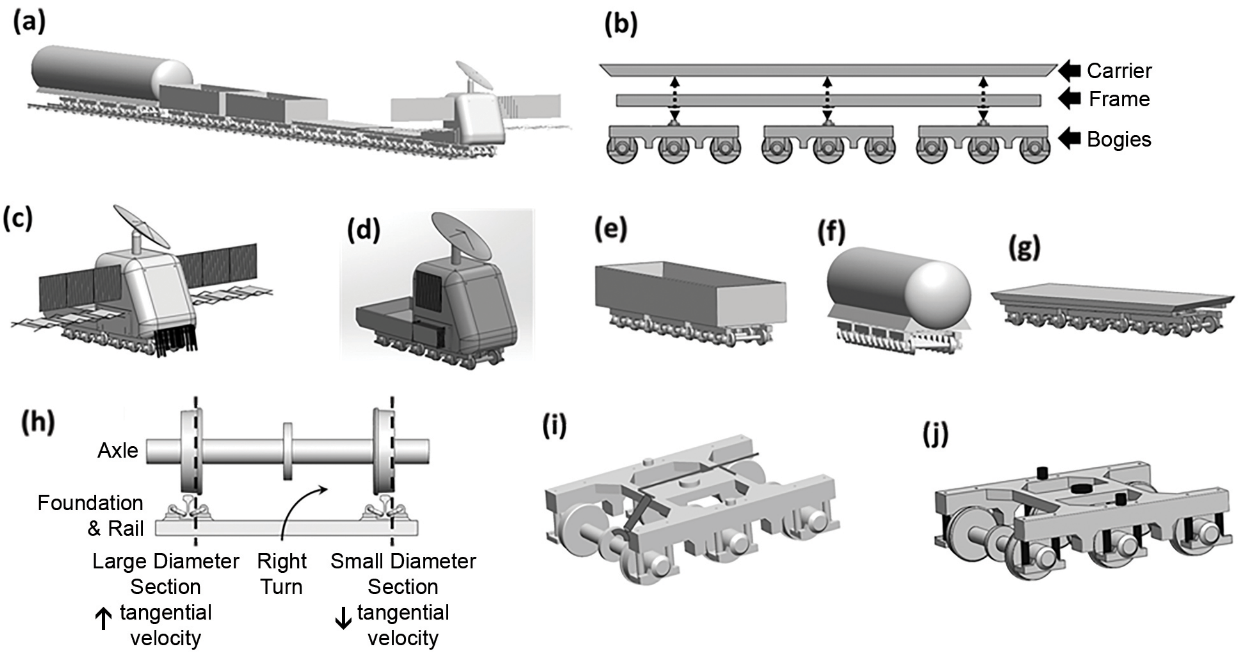


Figure 12.5. Integrated rail vehicles. (a) Example train consisting of an engine, two flatbeds, two hoppers, and a tanker. (b) The construction of a flatbed carrier with bogies, frame, and carrier. The Engine vehicle is shown in (c) day and (d) night mode. Standard hauler carriers are shown: (e) hopper, (f) tanker, and (g) flatbed. (h) Diagram of rail wheel turning. (i) Brake assembly on standard bogie and (j) suspension assembly on standard bogie. [Credit: Northrop Grumman]

Core to the engine's purpose is the motor and drive train controls subsystem. The electronics are housed in a closed compartment. The controls subsystem takes data from onboard sensors and external communications; communications are received directly from control stations on the rooftop antenna, rebounded from rail-side communications towers, or from in-orbit relay satellites.

Due to relatively high peak power versus low energy consumption, a battery powered engine is envisioned instead of electrified rails. Mounted to the side of the motor compartment are collapsible radiators and photovoltaic arrays, which will reduce stationary charging time when operating frequency increases. Deployed during the lunar day, the radiators offload thermal energy from the engine. On the front of the motor compartment is a brush to clear dust and debris off the rail line in front of the engine. The back tray of the engine transports small-size equipment and tools for mobile deployment. The weight capacity of this compartment will depend on the power output and mass of the motor.

The three main hauler carriers are:

1. The hopper. Transports extracted regolith from the mining site to warehouses or is used for extraction of oxygen and metals.

2. The tanker. Transports liquid oxygen fuel (LOX) from refineries to launch sites. A secondary purpose is the flexible transport of water or gaseous oxygen to areas outside the reach of the pipeline that runs alongside the rail.

3. The flatbed. A flexible carrier for the transport of goods not ideal for the hopper or tanker. This includes the deployment of construction equipment along the rail or transporting construction and maintenance materials such as sleepers, rail segments, and metal ingots.

The bogie frame has attachment points to universally connect with any of the carriers or lunar intermodal shipping containers. The hopper and flatbed use three bogies, the engine uses two, and the tanker uses four. The bogie features three subassemblies: wheel and axle, brakes, and suspension.

Each bogie has three axles, each with two wheels. The wheels are attached to the bogie frame with a wheel bearing. The wheels are designed with an upward taper to navigate turns without need for a differential drive. For example, on a right turn the right wheel will shift to the small diameter section, decreasing the tangential velocity, while the left wheel shifts to the large diameter section and increases the tangential velocity. Powered versions of bogies include motors and motor drive electronics, with an assumption of two motors per powered bogie.

The brake assembly is critical to maintaining a safe speed along the rail line (30 to 60 km/hr). On downhill sections, a portion of the excess kinetic energy will be recovered via regenerative braking. The brake assembly includes a controller in the engine and hydraulic lines with quick-connect lines through the couplers to bring brake forces to the individual carriers. Each axle has a brake piston that hydraulically actuates to push a brake pad into the brake wheel mounted on the axle. The brake wheel acts as a sacrificial piece on the axle that can be replaced, rather than have the brakes wear down the axle itself.

The suspension protects the bogie and carrier from major vibration or damage caused by rough lunar terrain. It includes both springs to absorb the kinetic energy and dampers to provide resistance to the spring's reaction force. The suspension assembly includes two separate subassemblies. The primary suspension connects the wheel and axle to the bogie frame. The secondary suspension connects the bogie frame to the carrier.

The coupler assembly is the attachment and detachment point for the carriers. Couplers use a three-stage connection inspired by terrestrial Scharfenberg couplers. Because the wheels are angled and have a positional uncertainty, the bumpers first provide rough alignment as the carriers come together. Next, a multijointed mechanical mechanism is activated to lock the carriers together. At this point forces can be translated through the coupler. The third and final stage of the connection is an actuated, dust-tolerant connector.[22] The connector features three pyramidal structures for fine alignment as the two halves are brought together. An electrical connection is made through the permeable membrane, to keep it free from lunar dust.

12.4.4 Rail Station Infrastructure

Rail stations serve as distribution gateways across connected infrastructure corridors and manage the autonomous operation of the fleet of rail carriers. Whether the service being offered is to move mass, data, power, or thermal energy, it must interface through stations and substations. The primary equipment also manages the autonomous operation of the fleet of rail carriers and station operations. The overall list of equipment is as follows:

- Comm/Power/PNT payload towers. Inputs and outputs to and from the Lunar Rail Network. Communications are primarily off the lunar surface, where wired distribution cannot reach. These towers also distribute power and data into the wired grid.
- Command and control equipment. Internal data management, control of the fleet, sensor data analysis of the fleet, management of station operations including loading and unloading, track switching, scheduling, and more.
- Traffic and payload management systems. Support systems such as switches, loading docks, cranes, and the carrier and engine maintenance and fabrication depot. This includes au-

tonomous systems used to perform loading and unloading of the trains and associated hardware such as chutes, hoses, and cables.

- Resource distribution infrastructure. The physical relay and storage infrastructure, including substations, power converters, data centers, storage tanks, and warehouses.

A construct for the maintenance and fabrication depot was evaluated next. This part of the traffic and payload management is critical to building and operating an economically viable lunar rail. This depot will support all pilot and operational system needs. The center will include fabrication equipment for manufacturing ISRU-derived metallic components and assembly and integration in a dust-mitigated environment. Before entering the depot, carriers will enter a multistep staging area to remove dust using active control measures. This will preserve a well-characterized and dependable environment for operations within the depot. These operations include the following.

- Manufacturing of components, such as bogie frames
- Assembly and joining of components, such as welding of axle assemblies
- Integration of assemblies
    - Installation of bogie suspension assemblies, brake assemblies, motors and control electronics
    - Mating of electrical connections
    - Maintenance of wear items and consumables
    - Replacement of brake pads
    - Loading and maintenance of hydraulic fluids
    - Restoration of wheel rims with additive manufacturing welders.

12.5 Scaling Study

A primary objective of the Lunar Rail Network study was to determine how this infrastructure concept would scale from a demonstration effort into a complete system with fully operational service. A five-phase plan of expansion, in a ten-year horizon to full implementation,[23] is laid out in table 12.1.

Table 12.1. Phases of development and expansion for the Lunar Rail Network

Phase	*Development Phase*	*Phase Activities*	*Years*
Predevelopment	Scientific understanding	Gap mitigation and fundamental science	2
1	MVE development	Nonrecurring engineering, manufacturing, assembly, equipment testing, and demos	2
1	MVE integration, test, launch, transit	Integration, test, launch, and transit to lunar surface	1
1	Phase 1 MVE	Construct rail of ~0.2 km, perform MVE Phase 1 demo.	1
2	Phase 2 MVE	Add dynamics, civil engineering, and wear test track to mature railroad architecture. Support early mining and foundry.	2
3	Phase 3 pilot	Expand to connect to high traffic launch site.	1
4	Phase 4 pilot	Add additional routes to other processing facilities around first settlement, scale toward full operational state.	1
5	Phase 5 operational expansion	Expand reach to additional settlements (investments justified for each addition).	3+

Key
MVE: minimum viable experiment

The ten-year plan includes early refinement of scientific understanding in terrestrial experiments, followed by development of the experimental system, called the minimum viable experiment (MVE). This scaling envisions an early demonstration (MVE Phase 1), then an architecture technology maturation (MVE Phase 2), before expanding into a two-step pilot rail network centered on a single settlement region (Phases 3 and 4), with eventual expansion into a fully operational system that spans multiple settlement regions (Phase 5).

The two-phase MVE performs the first testing in real conditions on the lunar surface. This will demonstrate the viability of broad resource mobility and develop understanding of the performance of the rail architecture over time. Phase 2 of the MVE avoids building significant rail route infrastructure that might need reworking if it does not deliver reliable performance under repeated usage. Like envelope expansion of an aircraft during testing, the rail system would be subjected to increasing speeds and mass transport loads and monitored for signs of degradation in performance. The mechanics of wear and dust in lunar environments will thus be evaluated to better define maintenance requirements and develop solutions.

Phase 2 will also support early resource extraction operations and settlement of the local region. Phase 2 requires two heavy-lift landings within a few kilometers that then build toward each other. Each set of equipment will build a separate half of what will become a test track loop. This loop will excavate a substantial amount of surface regolith for adjacent ISRU operations. It will also allow a train to continuously and repeatedly operate at various speeds and durations, without requiring a substantial rail network. The track will incorporate both the minimum safe radius at max operational speed (several hundred meters) and elevation gain and loss to maximum traction design points, to evaluate performance in slopes and dynamic performance in turns. Switches, sensors, and station data processing will be incorporated as necessary. Wear will be monitored in multiple locations. Inspection, maintenance, and repair operations and methodologies can be tested and refined on the test track loop.

Since ISRU equipment and potential fuel launches will require only limited deliveries from the rail system at this early phase of development, test trains can operate at a high rate of utilization to quickly generate data on performance and simulate many years of operational degradation. With 4 to 5 km of track and a train operating at 30 or 60 kilometers per hour, thousands of trips can be simulated in a single Earth month, accumulating years of simulated operation in a short time frame. Therefore, an evaluation timeline of eighteen months is sufficient to robustly demonstrate the longevity of the Lunar Rail Network architecture and to refine designs and maintenance methods to support decades of operational usage on the Moon.

Phases 3 and 4 build up the Pilot Lunar Rail Network. When completed, for the first settlement area it will deliver mass mobility at prices that rovers cannot compete with. These two phases start by connecting processing facilities to a dedicated, prepared launch facility.[24] As discussed in earlier chapters, locating a dedicated launch pad facility reasonably far from other facilities offers benefits, including avoiding risk of debris and dust impacting other lunar operations. It is anticipated that ISRU operations will expand significantly with the standup of a dedicated launch facility, which will greatly increase the amount of mass moved to and from processing sites.

Rail carriers for Phase 3 will resemble the operational design, including increased modularity and three or four bogies per carrier, compared to the two-bogie designs with fixed payload transportation assemblies used in the MVE phases. The increased scale permits more mass carried per railcar and for specific train configurations to be assembled for each trip. This will minimize single-use mass and maximize components fabricated with 100 percent in situ derived materials.

While Phase 2 will perform maintenance operations in an open environment, Phase 3 will include construction of a dedicated, environmentally controlled fabrication and maintenance depot. This will result in increased fabrication rates of components, electrical mates and bogie integration, and maintenance. This phase will evaluate uniformity of operational conditions and mitigate the risks of dust and thermal variation on fabrication and assembly.

Phase 4 will see an increased rate of construction from 1.7 km/month to 4.2 km/month, to create 50 km of new track in one year. This increase will be primarily accomplished by expanding from twenty-eight construction vehicles to sixty-two vehicles by Starship-aided delivery. This connects the initial processing facilities and launch pad facility to other sites of interest, such as additional mining sites, astronaut habitats, agriculture sites, or processing facilities.

Phase 5 commences when demand develops to connect the first settlement area to additional settlement areas in the south pole region. The construction rate must increase from 4.2 km/month to 11.1 km/month to build 400 km of additional track infrastructure. This requires doubling the construction fleet used in Phase 4. Additional rail carriers will also be built, but it is assumed that a single fabrication depot facility will be sufficient. Terrain navigation will become the primary challenge for Phase 5; engineering through and around substantial elevation changes to connect farther destinations will be necessary.

This infrastructure scaling study also considered likely bounding capacity analysis for sizing of the phased expansion and economic analysis. The current space business market must evolve into a market that relies on in situ lunar resources as a new paradigm to reduce operational costs and leverage new capabilities.

Many cost assumptions were made to obtain an overall investment estimate for the rail network.[25]

- Development cost of $30,000 per kg (equipment, detailed components)
- Development cost of $3,000 per kg (maintenance depot building)
- Cost of launch to Moon base of $10,000 per kg (~7x of the cost of a Falcon 9 to low Earth orbit)
- Cost of manufacturing metal parts on the Moon of $500 per kg
- Cost of manufacturing equipment on Earth of $5,000 per kg
- Cost of energy on the Moon of $100 per kWh
- Maintenance cost of 5 percent per year of manufacturing cost for infrastructure (twenty-year life), 20 percent per year for carriers (five-year life)

These assumptions differ significantly from other chapters, which consider current launch costs and energy costs. Inherent to lunar rail expansion is a substantial reduction in the cost of both launch and lunar energy. Both assumptions are within the realm of the possible given current cost trends, but more attention to scalable lunar surface power technology maturation is needed. Table 12.2 shows the conclusions of this analysis along with an average price per trip goal.

Table 12.2. Phase scaling and investment ballpark for the Lunar Rail Network

Parameter	*Phase 1*	*Phase 2*	*Phase 3*	*Phase 4*	*Phase 5*
Average trip length [km]	0.2	2.4	3.9	24	128
Average trip payload [kg]	200	5,000	32,000	45,000	83,000
Total Earth-launched mass by phase [kg]	16,100	25,300	64,200	90,000	167,000
ISRU metallic mass required [kg]	1,800	43,300	212,000	520,000	3,700,000
TOTAL estimated NRE [$B]	0.5–1.0	0.5–1.0	2.0–3.0	2.0–3.0	4.0–5.0
TOTAL estimated RE [$B]	---	<0.1	0.1–0.2	0.3–0.5	2.0–3.0
TOTAL Goal Avg Price per Trip [$M]	---	8.0	8.0	5.0	2.5
Mass price efficiency [$USD / kg-km]	17,700,000	660	51	3.4	0.23

Key
ISRU: in situ resource utilization
NRE: nonrecurring engineering
RE: recurring engineering

12.6 Conclusion

This chapter concludes with a look at cross-mass mobility and trip momentum cost efficiency. For Phase 2 and beyond, the cost per kg-km for transportation and the momentum (kg-km/minute) were evaluated. These were compared to estimates of existing and future rover vehicles, and recurring expenses for terrestrial freight vehicles. Figure 12.6 summarizes this analysis.

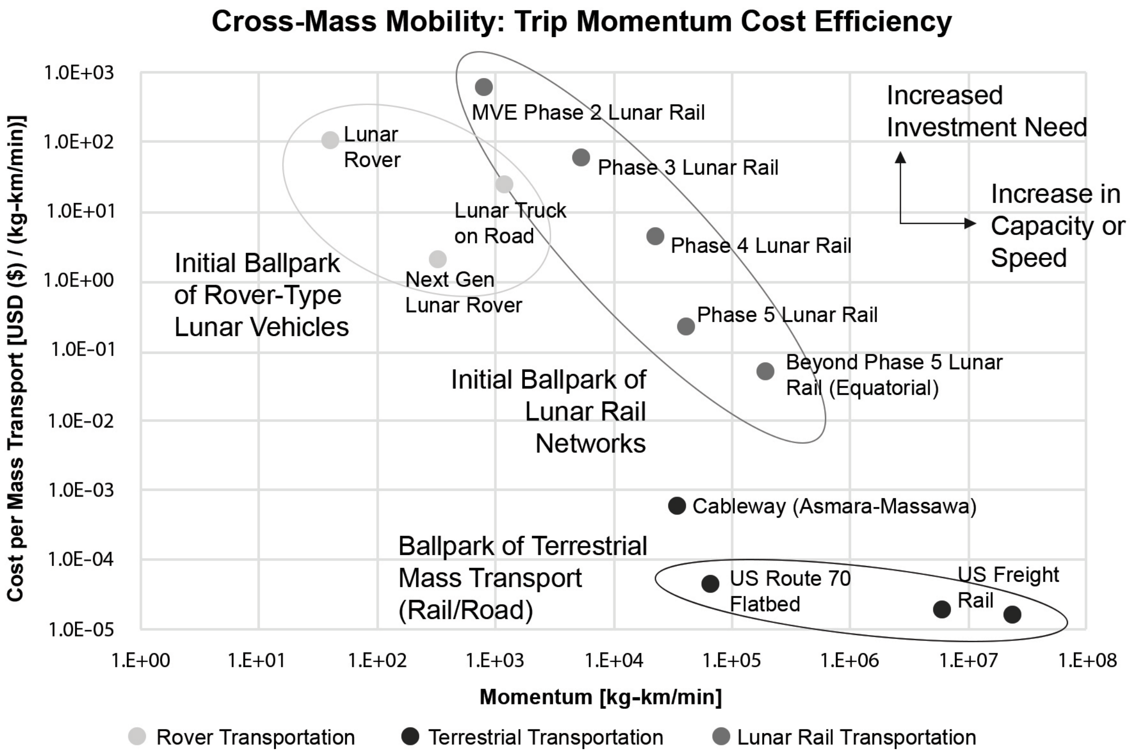


Figure 12.6. White space plot examining trip momentum cost efficiency for cross-mass mobility. [Credit: Northrop Grumman]

A sustainable lunar economy will need at least an order of magnitude increase in mass-mobility-momentum capability and at least an order of magnitude reduction in cost of mass mobility. Terrestrial rail systems have shown two orders of magnitude increase in momentum over truck freight and a substantial resulting cost savings per kg-km. Lunar rail will provide the same benefit and can move mass across the Moon at one to two orders of magnitude less cost than rover-based solutions.

This study has built a baseline for future work toward a Lunar Rail Network Infrastructure. The scope and potential for thriving lunar infrastructure are wide-reaching and present the opportunity for many supporting future works including research, providing services in a commercially viable manner, and supporting a long-term off-planet economy.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Colorado School of Mines.
2. Norwegian Geotechnical Institute.
3. Authors Floyd, Levin, Oberhausen, Singh, Kinsella, Fite, Lin, Moo, Snyder, Davidson, Nishimura, and Johnstone are from Northrop Grumman Systems Corporation.
4. Defense Advanced Research Projects Agency (DARPA).
5. This paragraph was authored by Stowe Symon, Marc Brodecki, Kyle McAlpin, Michael Sholl, Cassandra Parkos, Paul Wooster, Nicholas Cummings, and George R. Sondecker. All authors are from Space Exploration Technologies Corporation.

6. Williams et al., "The Global Surface Temperatures of the Moon."
7. Vanoutryve et al., "Analysis of Illumination and Communication Conditions."
8. Minow et al., "Radiation and Plasma Environments for Lunar Missions."
9. Department of Geophysics, *Apollo 14 and 16 Active Seismic Experiments, Apollo 17 Lunar Seismic Profiling*.
10. Department of Geophysics, *Apollo 14 and 16*; and Langer et al., *Advantages and Pitfalls of Pattern Recognition*.
11. Rao et al., "Effect of Annealing."
12. Ma et al., "Wear and Damage Characteristics of Rail Material."
13. Merstallinger et al., "Influence of Coatings and Alloying."
14. Analysis results from collaboration with Jeffrey Lince of Space Tribology Consulting.
15. Metzger et al., "Experiments Indicate Regolith Is Looser in the Lunar Polar Regions."
16. Mueller, "A Review of Extra-Terrestrial Regolith Excavation"; and Just et al., "Parametric Review of Existing Regolith Excavation Techniques."
17. Benaroya and Bernold, "Engineering of Lunar Bases."
18. Iai, "Scaled Experimental Study on Excavation of Lunar Regolith."
19. Although the ISRU and rail transportation concepts were developed separately, this overlapping in value chains (rail creating a monetizable input to ISRU) is an example of the importance of commercial-to-commercial sales in the lunar economy. Developing such connections has been a key focus of the LunA-10 program.
20. Waste regolith from an ISRU plant creates deoxygenated regolith (chapter 5), which can be an input to a metal foundry (chapter 6). The waste from the metal foundry can then be used for rail leveling and filling. This is an example of a value chain, where companies can buy and sell inputs and outputs from their services.
21. Jehn et al., "Lunar Site Preparation Requirements."
22. Herman et al., "Dust-Tolerant Mechanism Design."
23. Full implementation is defined as the end of Phase 4.
24. See chapter 9 for details on pad preparation to support repeated spacecraft takeoff and landing operations.
25. Colvin et al., "Demand Drivers of the Lunar and Cislunar Economy"; and Roberts, "Space Launch to Low Earth Orbit."

13

Cislunar Supply Hubs

Edited by Michael Nayak

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13.1 Introduction and Framing

Chapter 10 took the analogy of river cities such as Alexandria, Virginia, and built on it to posit infrastructure hubs on the lunar surface. However, river ports were not the only key to proliferation on the seas. They worked in tandem with deep-sea harbors. This chapter proposes the development and utilization of an in-space harbor as a central hub of infrastructure for lunar and deep space exploration missions.

Logistics is the lifeblood of any economy. A harbor in cislunar space can serve as a node between Earth and the Moon: a deep-sea port for in-space logistics. *Orbital logistics hubs* function as intelligent system buffers for inbound and outbound freight. The linking of multiple logistics nodes creates transport networks where the individual legs of the network can be separately optimized for volume, rate, and transport method. The examples of marine shipping, ground freight, and passenger air-travel all feature analogous expressions of nodes and legs, such as ports, airports, and warehouse distribution centers. Suboptimization in these systems is then observable in the variety of vehicle types, scales, and associated transport legs. All these systems, however, assume some degree of intermodal cargo (e.g., parcels, bulk, passengers) and repeat service (i.e., reusable vehicles).

To date, orbital logistics rarely include any kind of intermodality or reusability. Modern spacecraft instead are largely disposable vehicles with custom payload integrations. At certain scales of orbital transport traffic, this paradigm is cost-limited by nonrecurring engineering. The recent evolution of launch vehicles toward reusability creates an opportunity to redress the spacecraft paradigm and build orbital transportation networks analogous to marine and ground freight.

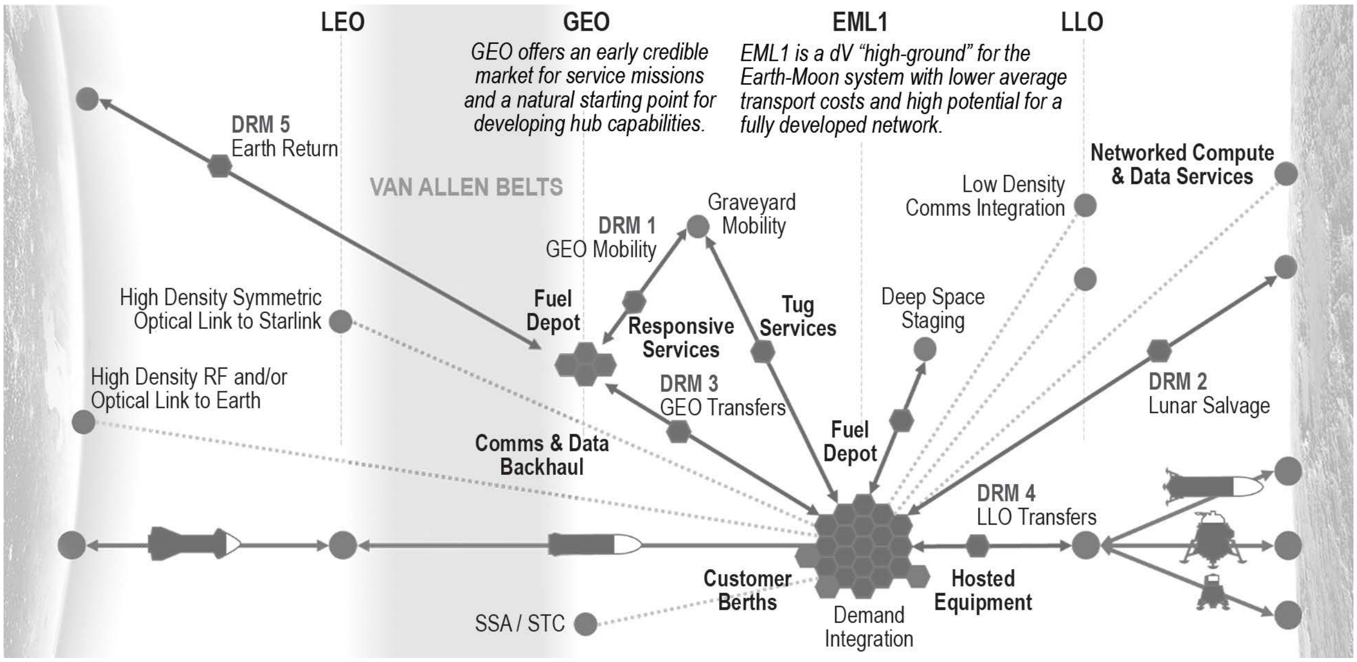
An orbital harbor, like its marine equivalent, acts as a network buffer to integrate large-volume inbound traffic and then redistribute it to small-volume outbound destinations. In the terms of a nodal network, this decouples utilization constraints and stabilizes outbound delivery rates against inbound variation. In turn, this creates responsive on-demand cargo delivery.

The benefits of aggregation for the lunar surface have been discussed in chapters 10 and 11. The same advantages exist in space. Using today's state of the art for docking and cargo transfer, the concept of spacecraft aggregation allows the harbor-as-a-buffer to scale with network traffic.

How might this aggregated hub be created? The answer begins in a base resource already in play: upper rocket stages bound for the Moon.

Today, an upper stage must deliver its payload into translunar injection and then be passivated for end of life (EOL). The existence of a cislunar hub creates a new paradigm, moving away from satellite EOL toward a symbiotic satellite "retirement." Rocket stages or spacecraft can drop off their lander or satellites in lunar orbit and then take themselves to a cislunar harbor. Arriving spacecraft would plug into the harbor and aggregate these resources. While a rocket stage or satellite has remaining fuel, data, communications, edge computing, or solar power, those can be repurposed as sharable resources to be used across a hub in a harbormaster model.

Aggregation is analogous to a distribution center; it allows payloads and commodities to accumulate, be reallocated, and then be redeployed on-demand. Unlike trucking, there is no need for a fixed warehouse. Instead, the capacity and functionality of the aggregation grows with every docked spacecraft, and every docked spacecraft doubles as a fleet vehicle. Every deployed spacecraft similarly has the potential to become the nucleation point for a new harbor or service destination.



Key

DRM: design reference mission	LEO: low Earth orbit
dV: delta-V (propellant)	LLO: low lunar orbit
EML1: Earth-Moon Lagrange point 1	SSA: space situational awareness
GEO: geosynchronous orbit	STC: space traffic management

Figure 13.1. Vision of a cislunar logistics hub across multiple orbital regimes. [Credit: Firefly Aerospace]

Figure 13.1 shows one vision for a network of logistics hubs across multiple orbit regimes. As the hub grows with more spacecraft, this becomes the home of services such as sensors for space domain awareness and refueling or even commercial space tourism.

Key architecture features include: (1) intermodal interfaces for spacecraft and cargo, (2) inter-craft commodity sharing, (3) networked communications, (4) intelligent coordination, and (5) disaggregated/aggregated configurations. At its core, the harbor serves as a strategic nexus, facilitating spacecraft assembly, refueling, maintenance, and resource magnification of power, communications, and edge computing capabilities amid the vast expanse of space. They create freight and harbor services to power the lunar surface and orbital lunar economy. While these harbors may ultimately support human life (akin to gas stations and roadside motels), in their early stages, they will function as autonomous robotic ports catering to the needs of launch and space vehicles shuttling between Earth and the Moon.

By providing a centralized platform for mission planning, execution, and collaboration, such orbital hubs enable expeditions farther into the cosmos, foster international cooperation, and leverage collective resources toward shared scientific or economic goals.

13.2 Overview: The Unit Spacecraft

The ideal location for a harbor depends on a combination of strategic factors. For example, for propellant consumption, proximity-to-service-destination is the largest efficiency factor. With disparate services, the ideal location may shift as traffic grows. For a lunar economy that includes end-to-end transport services between the Earth and the Moon, the topological "high ground" locations are EML1 and EML2.[5] Together with the associated halo orbits, these have the lowest average delta-v (ΔV, propellant) requirements for reaching other destinations in cislunar space, making them natural build sites for a cislunar transport network centered on robust cargo demand at the Moon.[6]

Aggregated spacecraft that form the core of the hub and provide essential harbor services are ideally identical or similar in design. These will be referred to as *Unit Spacecraft*. All other dissimilar spacecraft that dock with the hub or a Unit Spacecraft are considered *Customer Spacecraft*.

For the analysis in this chapter, the Elytra orbital spacecraft from Firefly Aerospace forms the basis for the cislunar hub architecture, sizing assumptions, and a common Unit Spacecraft definition. Deliberate additions or adjustments to that assumption are identified, as appropriate. For the remainder of this chapter, the *Orbital Hub* will refer to a collection of four Elytra spacecraft aggregated together. Following marine freight terminology, physical goods within the logistics network, including propellant, are included in the blanket term *cargo*. The associated terms of *bulk cargo* and *container cargo* can be applied to fluid transfers and hardware transfers respectively.

The critical functionalities for Unit Spacecraft aggregation have been identified in the following list:

1. Androgynous docking. Allows any two spacecraft to dock and reconfigure at multiple population scales.
2. Robotic arms and connections. Allow the remote transfer of goods and assisted docking.
3. Intermodal containers. Allow transferable cargo between platforms.
4. Orbital refueling. Enables mission longevity and obligatory service markets.
5. Autonomous decisions. Allow safety-critical management in real-time without latency delays.
6. Distributed ledgers. Allow recordkeeping for non-tamperable transactions.
7. Networked operations. Allow collective cooperation for resource sharing.
8. Modular power. Allows aggregation growth at larger population scales.

Aggregating spacecraft and the transfer of cargo requires robotic manipulation systems capable of regular traversals across spacecraft. The power and maintenance demands for robotic arms incentivize slower operation and near-continuous use. Chapter 8 (figs. 8.1 and 8.2) discusses grappling interfaces for robotics that may benefit Orbital Hub management.

Mass budget assumptions include separation systems for launch stacking (45 kg[7]), docking and grapple interfaces (twelve units at 1.5 kg each and 14.7 kg of support bracketry), a robotic arm (80 kg), and features for relocation of solar panels and comm systems as new aggregate formations are created.

13.3 Propellant as a Service: Unit Spacecraft Refueling

Refueling at the Orbital Hub enables a "maneuver without regret" paradigm for customers seeking high-thrust maneuvers with low regard for fuel consumption. To provide in-space servicing, the Orbital Hub must host a variety of propellant solutions, both as consumables for the Unit Spacecraft and as cargo for Customer Spacecraft. Chemical propellants such as hypergols are obligatory for the early Orbital Hub to host due to their widespread usage, thermal resilience, low freezing point, and moderate transfer pressure. Elytra, in particular, features a monomethylhydrazine/nitrogen tetroxide (MMH/MON-3) bi-propellant architecture, with a 2-meter-diameter cross section.

The Unit Spacecraft itself is the primary customer for refueling, as it enables tug capabilities necessary to service the mobility needs of other spacecraft. This means that any Unit Spacecraft at the Orbital Hub can be deployed to dock, grapple a customer satellite, change its orbit, and then detach to service another customer.

As the Orbital Hub evolves, Unit Spacecraft will need to feature electric propulsion to stay competitive. The advantages of high-specific impulse (Isp) from electric propulsion are best utilized for long transfers above the radiation belts, such as from the Earth to the Moon.

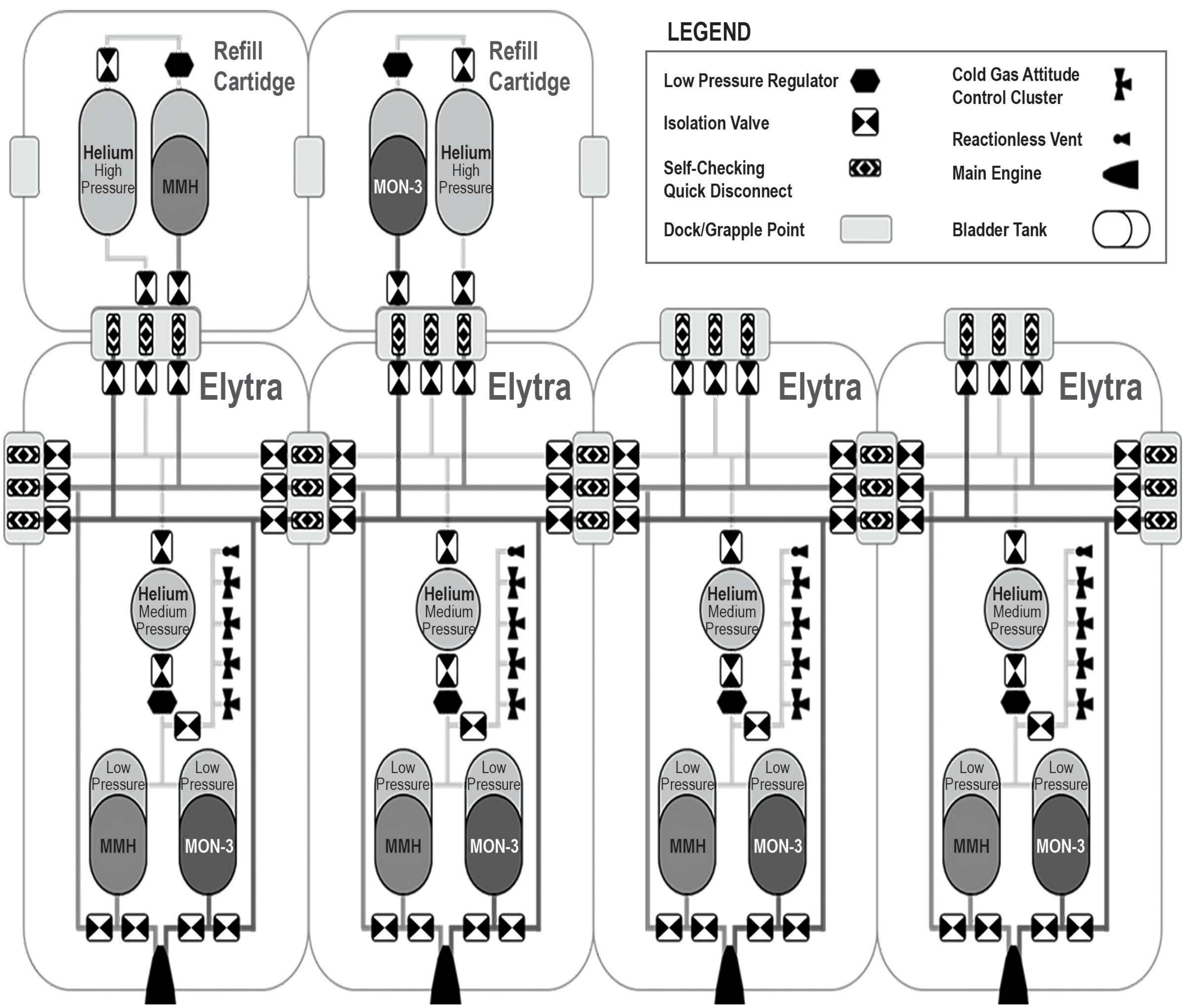


Figure 13.2. Conceptual flow diagram for a networked blowdown system of containerized propellant. [Credit: Firefly Aerospace]

The central refueling concept for the Unit Spacecraft, or any compatible Customer Spacecraft, is a cartridge-delivered blowdown system (fig. 13.2). While this flow diagram is based on the Elytra's MMH/MON propellant architecture, the principles presented here can be applied to any storable liquid propellant. Refueling solutions that require high-pressure transfers, including high-pressure pressurant recharging, were intentionally excluded as a near-term solution due to the complexity and power demands that exceed the current state of the art for orbital robotics. Similarly, cryogenic propellants are not reliable for indefinite storage.

The blowdown system proposed in figure 13.2 uses cartridges prefilled on the ground with propellant and high-pressure helium. For reliability and hazard management, all propellant systems are bladdered. A typical refilling procedure would be to isolate and vent the pressurized bladders of the target vehicle through a momentum dump or a reactionless vent. The Unit Spacecraft would need to feature networked plumbing to allow the transfer of propellant from any cartridge to any docking interface within the aggregate. This means flow paths can be selectively opened between the source and target tanks, across multiple spacecraft, with the cartridge pressurant providing the working force for delivery. If all network isolations are commanded open, the entire system will equalize in commodity distribution across all spacecraft. The same cartridge concept can be applied to pressurized gases such as helium, nitrogen, and xenon. Due to the relatively low working pressure for electric engines, a xenon cartridge would benefit more from being directly hosted on the Consumer Spacecraft than transferred along networked plumbing.

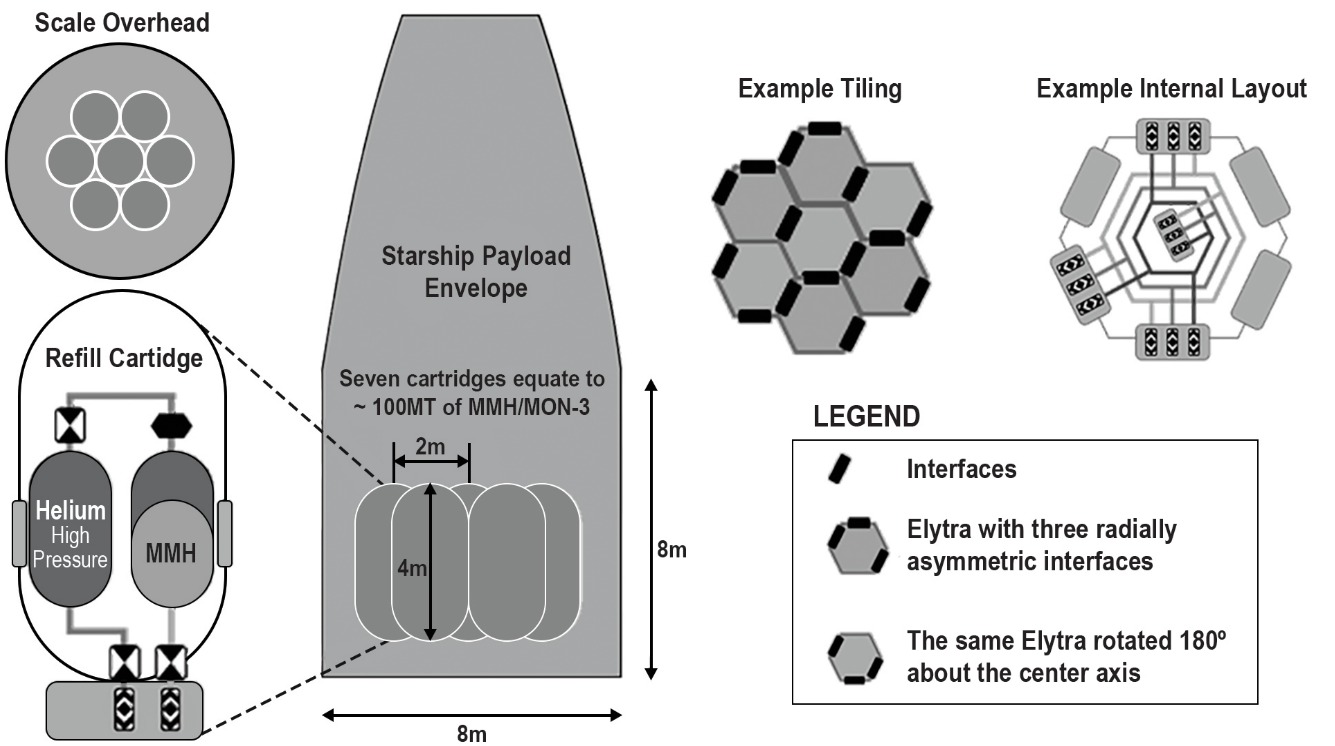


Figure 13.3. (Left) Containerized propellant delivery with 100 MT capacity vehicle. (Right) As few as three interfaces complete a fluid network with no loss of open tiling positions for growth. [Credit: Firefly Aerospace]

Refueling introduces considerable hazards for pressurization and combustion, many of which require the mass penalty of redundancy. This creates an incentive to minimize interfaces, seemingly in direct conflict with the concept of open aggregation. Asymmetric layout solutions reduce the total number of interfaces while preserving the ability to aggregate the same number of spacecraft (fig. 13.3, right). Figure 13.3 presumes a hexagonal representation of the Unit Spacecraft. Growth principles for aggregation as they relate to size and planform are discussed in a later section.

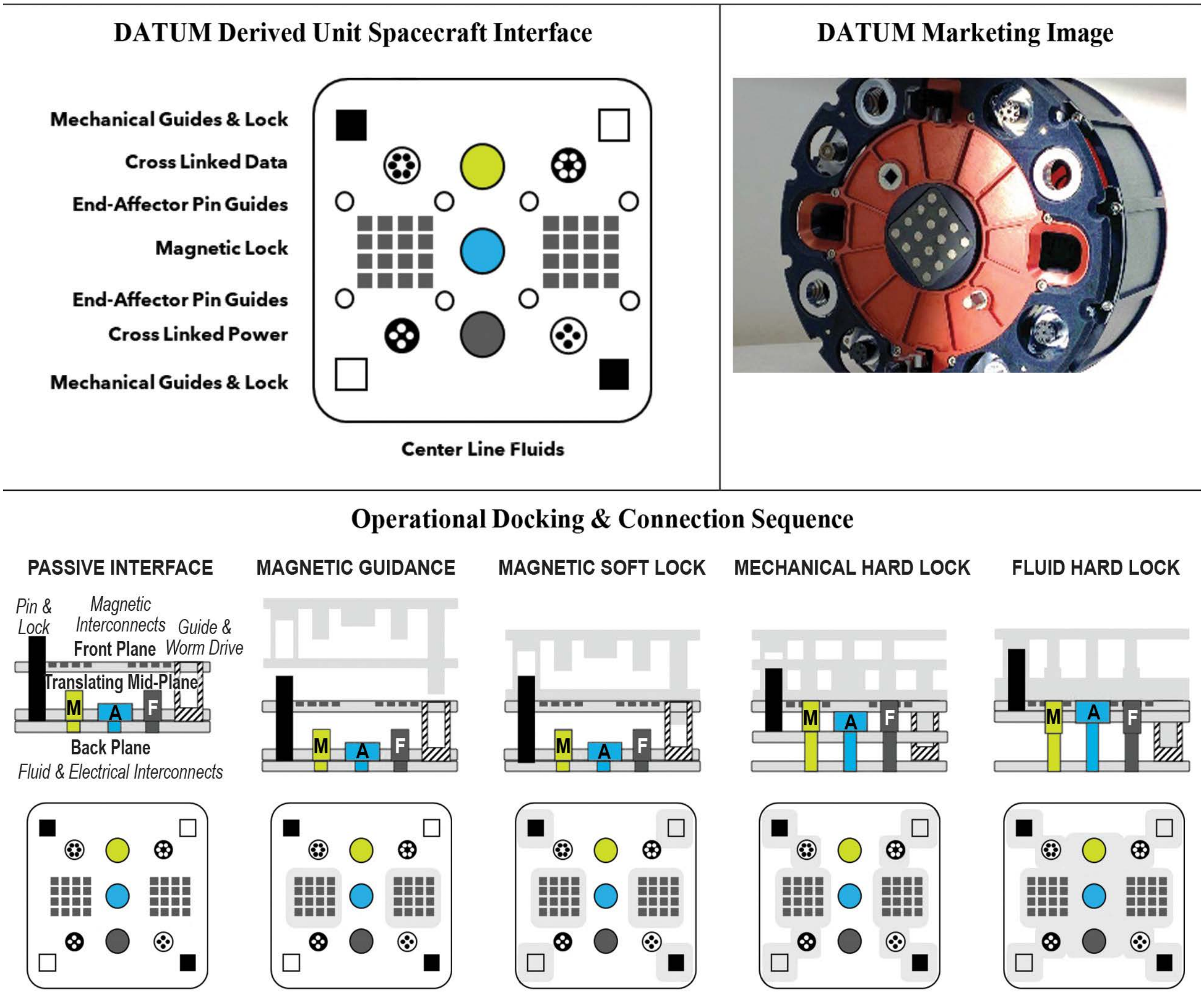
Circular or hexagonal spacecraft planforms can accommodate up to six radial interfaces for docking and fluid transfer. However, customers require only one interface to receive commodity transfers, while Elytra requires only two interfaces to serve as conduit pass-throughs and one polar interface to receive refill cartridges. The Elytra Unit Spacecraft holds ~225 liters (L) of propellant storage and 75 L of pressurant storage; a cartridge such as that in figure 13.3 (left) would hold approximately 3,000 L of propellant and 1,000 L of pressurant. Another consideration that favors storable cartridges for propellant transfer is the "empty gas can" problem. Regardless of how propellant is transferred, "tanker" deliveries are mass-incentivized to have an empty tank after delivery. That incentive will persist until the network is congested enough to require multiple refueling destinations in close orbital proximity. Containerized propellant transfers simplify the refueling architecture by eliminating pumping and the need for docking. Containers can be dropped off on orbit to be collected later by separate spacecraft, thus decoupling outbound traffic scheduling from the on-orbit scheduling. Containerized propellant also allows altering propellant capacity of compatible spacecraft and recycling of hardware that would otherwise be destined to become orbital debris.

There are unique considerations to the local orbital topology at EML1. Within the halo orbits, stationkeeping penalties are smaller the closer a vehicle is to the center of the Lagrange sphere. The "lower" halos are therefore preferred for long-term occupation, while the "higher" halos are preferred for collections and drop offs. Most maneuvers between halo orbits can be accomplished for <1 meter per second of ΔV, given sufficient dwell periods.

There are two noteworthy scenarios for disposal. In the case of a Starship-type vessel regularly cycling between EML1 and LEO, the empty propellant cartridges can be collected and returned to Earth for refill and refurbishment. This same scenario is directly applicable to a GEO Hub serviced by a launch vehicle. At EML1, tanks could be disposed of by inserting them into a lunar impact trajectory before the spacecraft returned to the aggregate. Provided the Earth return includes an aerobraking maneuver, both scenarios require a similar magnitude of ΔV,. A more detailed economic analysis is needed to explore the business viability of return-shipping the empty tanks. Lunar disposal is partially captured within the design reference mission (DRM) studies for network growth, discussed in section 13.5.

13.4 Aggregation Interfaces

Given the robotic, aggregation, and refueling needs of the Unit Spacecraft, the next consideration becomes the interface required to achieve it. Several companies are exploring interfaces to enable in-space servicing. Presented here is a functional concept derived from a Voyager Space interface product, the "Docking Anchoring and Towing Universal Match-plate" or DATUM.



Key
A: androgynous
F: female
M: male

Figure 13.4. Androgynous staged docking solutions enable separation of hazardous mating from docking. [Credit: Firefly Aerospace]

The interface features androgynous docking, fluid interlinks, and dual-mode electro-permanent magnets (EPM). With an EPM system, polarity reversal can be commanded. This creates a staged docking solution; two spacecraft can be soft docked magnetically prior to initiating a mechanical latching. Additionally, the EPM will retain its polarity state and holding force even in the absence of power. The staged docking allows fluid and electrical connections to be mated independently of spacecraft mating.

Any aggregate docking solution must contend with symmetry and crosslinking. Asymmetric layouts lose the advantages of androgyny. Crosslinking connection pairs can create symmetry at the cost of mass and complexity. The crosslink of electrical connections is preferred over fluid connections, due to significantly lower mass penalties. A DATUM-derived interface that accounts for the specific symmetry concerns of aggregation reconciles these attributes (fig. 13.4). A translating midplane creates a compact servicing connection for commanding fluid and electrical mates separately from docking. A similar product from Voyager Space, MagTag, features EPM technology without docking and fluid interfaces. Interoperability between a smaller EPM-only interface and the larger docking interface creates a diversity of attachment points for robotic arms to “inchworm” (see section 8.3) and move freely between interfaces and cargo.

13.5 Growth of the Aggregate Cislunar Hub

Given a Unit Spacecraft definition, a model within a physics-based event simulator was constructed to explore the dynamics of the Orbital Hub. An initial rendering of the Hub focuses on four spacecraft aggregated together (fig. 13.2), hosting propellant storage and performing robotic transfers. A population of four spacecraft at the GEO Hub is relatively immune from most zoning considerations. As the Hub grows, however, hazard management has a larger impact on the arrangement and configuration of aggregated spacecraft.

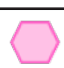
Square, pentagonal, hexagonal, and octagonal tiling were explored. A hexagonal tiling paradigm restricted to one plane presents several advantages:

1. It is applicable to common circular spacecraft planforms.
2. It achieves total coverage within a plane.
3. It is stronger against in-plane forces.
4. Planar growth maintains access in the z-direction for utility and transfers.

Aperiodic tiling (spacecraft of different sizes), spinal fractals, and Bernal stacks were identified as areas of study for significantly larger orbital populations. Aperiodic tiling is a natural growth pattern for a high diversity population. Bernal stacking presumes no aggregate diversity, thereby allowing for complexity through layered arrangements.

For smaller near-term populations, hazard management incentivizes the creating of zoning rules for aggregated or visiting spacecraft (fig. 13.5 and table 13.1). Zoning rules control the relative internal organization of the Orbital Hub. This prevents self-organizing spacecraft from collecting into formations that inherently limit their hazard response or prevent customers from freely undocking. To simplify early planning, the assumed planform for the Hub population is a 2 m spacecraft with six equally spaced interfaces. This is represented as a hexagonal envelope or tile but is also equivalent to a circular planform. Also studied under LunA-10, though not presented in this *Field Guide*, were double-digit populations and the implications of larger aggregation configurations.

Table 13.1. Early growth for a single-digit population aggregate demonstrates effects of zoning tiers. [Credit: Firefly Aerospace]

Zoning	*Key*	*Description*	*Zoning Rules*
Tier 0		Customer berths	Tier 0 units must be always separable within the plane and are permitted only one connection point to the aggregate
Tier I		Hazardous leases	Tier I units must be separable, and no separation of a Tier I unit may subdivide the Tier I or Tier II groups
Tier II		Nonhazardous leases	Tier II are permitted to be non-separable and/or fully enclosed within the aggregate

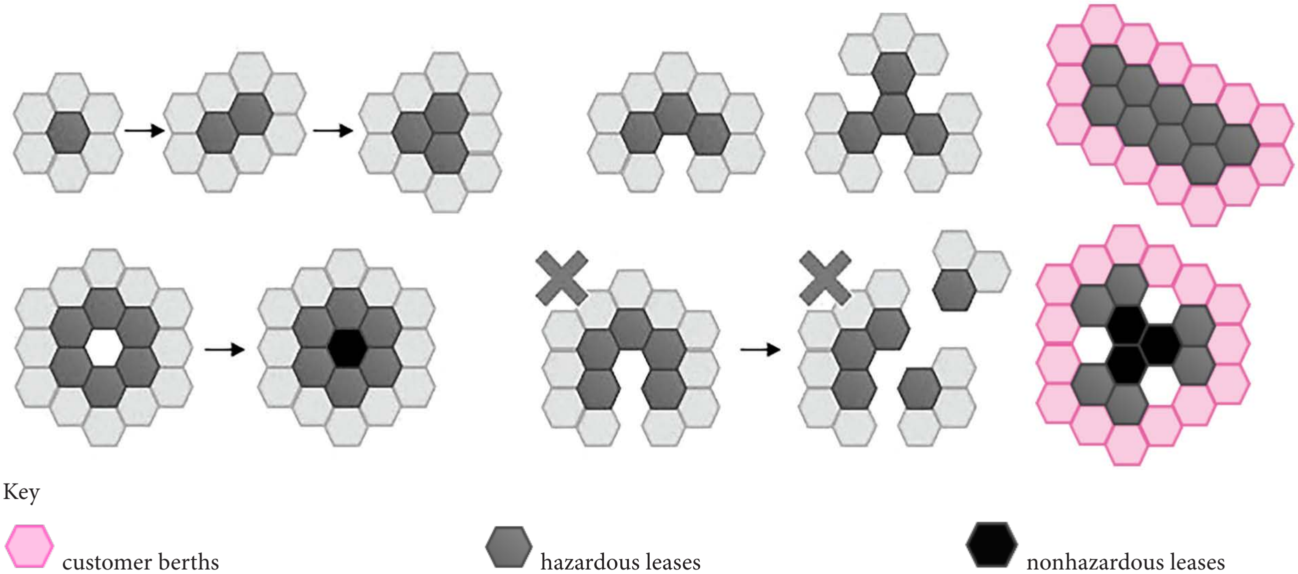


Figure 13.5. Zoning rules for continued aggregate growth. [Credit: Firefly Aerospace]

Wherever an Orbital Hub is located, it must contend with the induced and natural environments: internal dynamics, thermal view factors, solar power, orbital traffic, micrometeorite and orbital debris (MMOD), solar wind, and radiation. Debris can strike from any direction with higher probability for high-energy impacts in the orbital plane. Higher orbits such as EML1 may be threatened by seasonal activity related to comet orbits that intersect with the Earth's orbit about the sun. EML1 orbits do not benefit from the Earth as a shield against galactic cosmic rays. Like debris, the implication of radiation is the need for relative positioning of dense materials to shield sensitive systems. The richer an aggregate becomes in fluids (e.g., water), the easier this becomes.

13.6 Summary and Conclusion

An aggregated spacecraft Orbital Hub at EML1 is a feasible way to provide a waypoint and services to a lunar economy, in an organically scalable way, with the flexibility to match demand. Ultimately, the timing and optimization of logistic supply lines are what unlock the value of a hub, driven by the number of missions and total cargo mass.

Table 13.2. A variety of core services can be hosted by increasingly complex and robust aggregates. [Credit: Firefly Aerospace]

Service type		*Standard Service*	*3rd party Service*	*Commission rate*	*Rate service*	*Subscription Service*	*Market studies*	*Future studies*
Material services								
Cargo services	Bulk cargo	•	-	•	•	-	Cost analysis focused on common payload cargo & MMH/ MON-3 bulk cargo, with some analysis of additional fluid bulk cargoes	Future studies should include manufactured goods. Salvage materials, & regolith-derived raw materials (e.g., refined metals & volatiles)
	Break bulk cargo	•	-	•	-	-		
	Container cargo	•	-	•	-	-		
Industrial services	Orbital refinery	-	•	-	•	-		
	Orbit reclamation	-	•	•	•	•		
	Orbital manufacturing	-	•	-	•	-		

Service type		*Standard Service*	*3rd party Service*	*Commission rate*	*Rate service*	*Subscription Service*	*Market studies*	*Future studies*
Harbor services								
Tug vessel services	Orbital transfers	•	-	•	-	-	Cost analysis focused on rentals, provisioning, salvage sales, tender services, & tug services, including disposal and deorbit	Future studies should include pricing for the exchange of momentum, termal, data, & storage
	Orbital inspections	•	-	•	--	-		
	Orbital towing & servicing	•	-	•	-	-		
Dock & berthing services	Slip/hosting rentals	•	-	-	-	•		
	Storage rentals	•	-	-	-	•		
	Date & power provisions	•	•	-	•	-		
	Momentum provisions	•	•	-	•	-		
Virtual services								
Relay services	Low density short-range comms	•	•	-	•	•	Cost analysis focused on communications, data backup & security, PNT services, space traffic management, ledger management, & fractionation	Future studies should include more complex SaaS and CaaS services such as hosted CNN/DNN, virtual machines, data reduction, edge compute, & cyberthreat monitoring
	Low density long-range comms	•	•	-	•	•		
	High density long-range comms	-	•	-	•	•		
	Data storage	•	•	-	•	•		
Remote data services	Software as a service (SaaS)	•	•	-	•	•		
	Compute as a Service (CaaS)	•	•	-	•	•		
	Traffic/situational awareness	•	•	-	-	•		
	Space weather monitoring	•	•	-	-	•		

Key
CNN: convolutional neural network
DNN: deep neural network
MMH: monomethylhydrazine
MON-3: nitrogen tetroxide
PNT: positioning, navigation, and timing

The development, launch, operations, and maintenance costs of the Orbital Hub are significant factors. Estimated revenues from Hub services must be plausible, adequate, and timely. Refueling and transport services are likely to be the major drivers in determining Orbital Hub profitability.

In the meantime, the following technology areas are recommended for further development: federated spacecraft architectures, certification for automated rendezvous proximity and docking, modular power architectures, in-space swappable tank interfaces, and in-space liquid fuel transfer.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Scholtes, Spruce, Ferring, Lund, and Gordon are from Firefly Aerospace.
2. Authors Welsh, Ramadoss, and Elson are from Tensor.
3. Authors Cyrus and Gemer are from Lunar Outpost.
4. Defense Advanced Research Projects Agency (DARPA).
5. Earth-Moon Lagrange Points 1 (L1) and 2 (L2).
6. ΔV (pronounced delta-V) is a measure of propellant usage. It is a measure of the impulse per unit of spacecraft mass to perform an orbital maneuver.
7. Baselined against Payload Adapter System of nominal size (PAS 2624). "Payload Adapters and Separation Systems," *Beyond Gravity*, 2–3, https://www.beyondgravity.com/.

14

The LunA-10 Analytical Framework

Edited by Michael Nayak

Contributing authors: Elizabeth Hyde,[1] Shawn Britton, Olive Stohlman,[2] Luke Sauter,[3] Daniel Kulp,[4] Katelyn Eppich,[5] Curtis Boyd, Joshua Daniels,[6] Ashley Batjer, Lee Pele,[7] Christine White,[8] and Michael Nayak.[9]

14.1 Introduction and Framing

By now, the informed reader will have discerned several dozen connections among the commercial services discussed in the previous chapters. This chapter draws these threads together, to knit a cohesive lunar framework out of those disparate pieces.

It is *a* framework, not *the* framework.

The frameworks presented in this chapter will be a snapshot in time of our thinking.[10] Reality will diverge from this point on. It is the hope of the authors that this framework can serve as a fiducial mark of progress: how did what happened measure against what was possible, given the technology of 2025? This framework is also being used by DARPA as a reference design from which to derive other things of use to the lunar economy: interoperability standards, new business cases, productivity and scaling measurements, even financial engineering and strategic norms for international players working together.

When you can envision the future: you can create it. This is one possible future.

Everything presented thus far has been generalized to the maximum extent practical. An architecture that is not rooted in technology is just empty figures. This chapter is necessarily focused, therefore, on specific details. There are other power beaming companies than Fibertek, other lunar landers than Starship, other Comms/PNT products than MUST. The LunA-10 companies and their products discussed in this chapter are representatives of a much larger ecosystem. The numbers presented are a function of those specific technologies and are examples of what's possible by *any* launch or positioning, navigation, and timing (PNT) or power company—perhaps even a bar to exceed.

While architecting a lunar economy may seem like the stuff of science fiction novels, historical analogs can guide the process. In the nineteenth-century American West, a series of government-funded exploration missions led to commercial ventures moving in and establishing trade routes, which eventually created the conditions for mass migration events that would forever change the American economy. While the regulatory and sociopolitical environments have changed in the past two hundred years, the technical, logistical and economic developments during westward expansion provide a blueprint to how a self-sustaining economy can be born out of nothing in a new land; this time, the Moon.

Using this blueprint, four distinctive stages of development were identified; (1) the Exploration Age; (2) the Foundational Age; (3) the Industrial Age, where economic zones are connected into an industrial base; and (4) the Jet Age, where rapid transit enables a global economy.

14.2 The Exploration Age

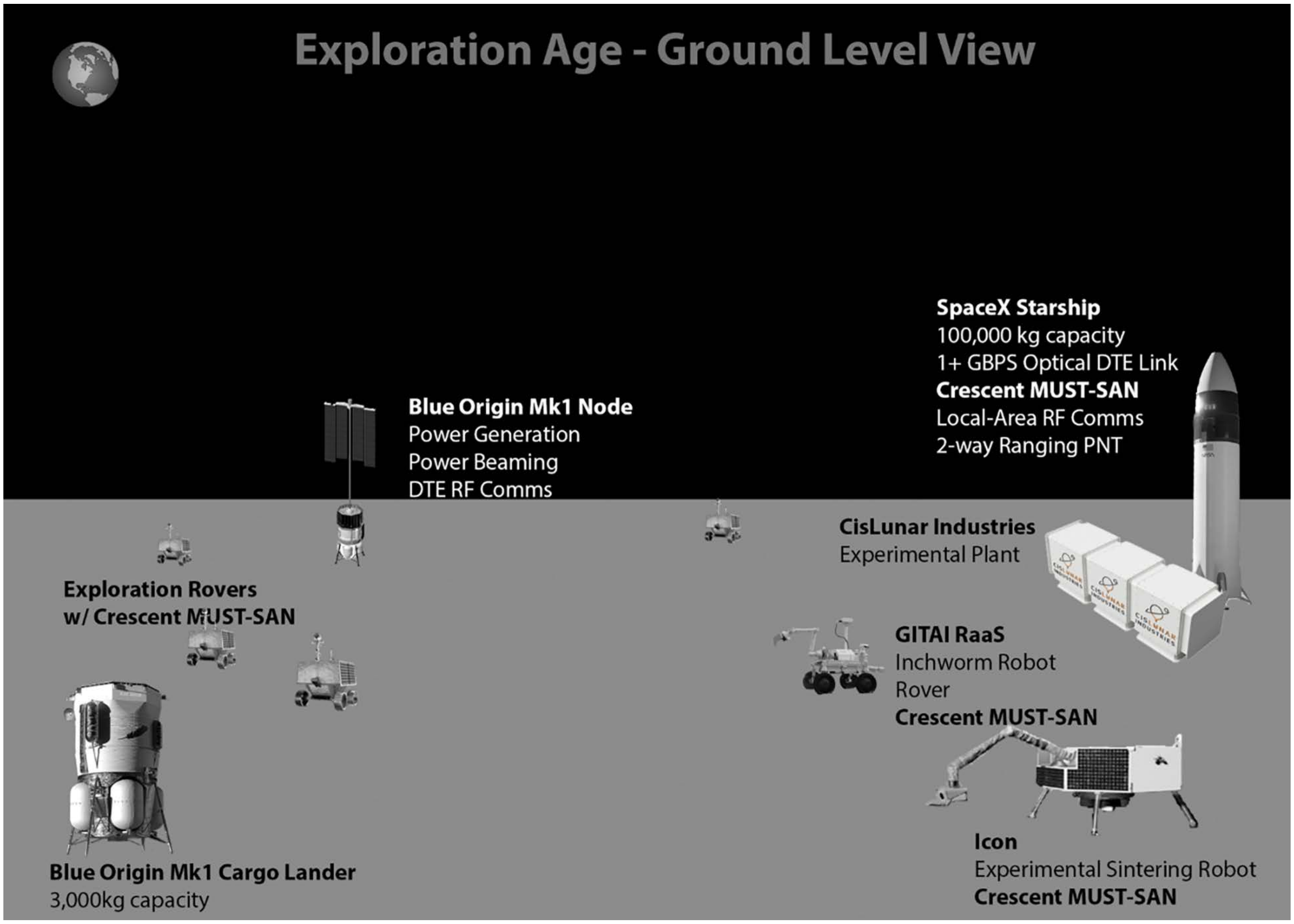


Figure 14.1. The state of play during the Exploration Age

Today, the lunar economy is in its Exploration Age. Government-backed missions have dominated the landscape, with private industry poised to take a larger role as the barrier to entry lowers. As with the mountain men of old, these early lunar missions are narrow in focus, with one-of-a-kind hardware. They are designed to be fully self-sufficient, with no reliance on infrastructure or resupply of any kind. These missions are also typically short in duration, without the ability to survive multiple lunar nights. In more mature technology areas like communications and launch, commercial activity has taken larger steps, but much of the activity in the Exploration Age is to test and demonstrate future technologies, survey the landscape for resources, and prepare trails that will be refined in a subsequent age.

Figure 14.1 illustrates one state of play, using the LunA-10 consortium of companies, for the Exploration Age in the five years after the publication date of this *Field Guide*. It is worth noting that none of the illustrated companies or their competitors have successfully demonstrated a commercial service on the surface of the Moon,[11] so even this early state of play is notional.

Exploration Age missions are predominantly lander-based. Landers arrive with equipment and built-in infrastructure to support local operations (akin to the forts of old). The landers included have endemic, non-extendable local and direct-to-Earth (DTE) communications, ranging-style navigation, and power. This limited infrastructure can support close-proximity, short-duration rover prospecting operations and some static facilities, such as small-scale in situ resource utilization (ISRU) experiments.

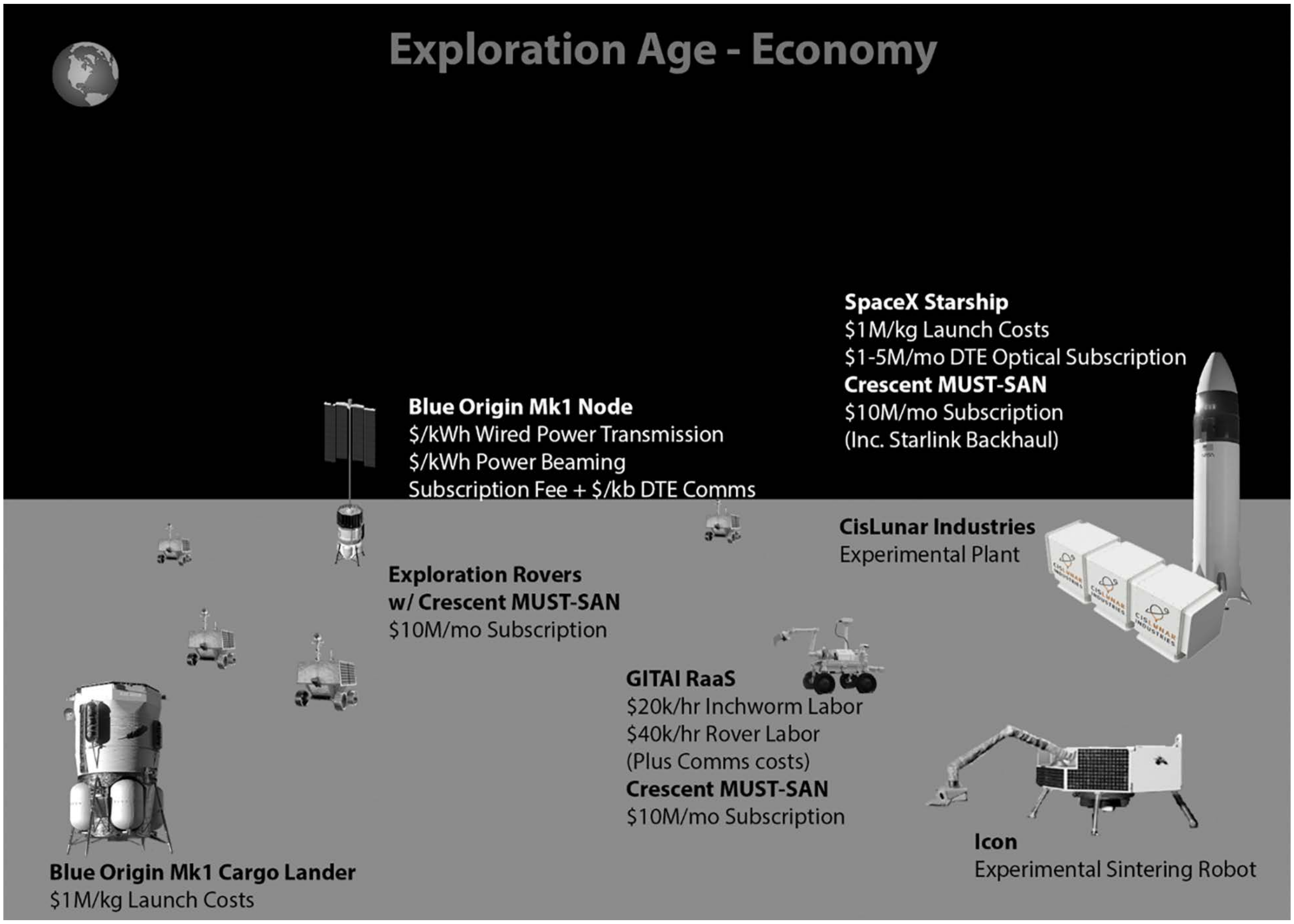


Figure 14.2. Cost of services during the Exploration Age

From an economics point of view, most of the capital investment in the Exploration Age is in future technologies (fig. 14.2). While high-level prospecting has been performed by government entities as a global service, as with terrestrial mining, the final defining of reserves will depend on targeted surveys by private entities.[12] Economic exchange of data in this age is expected to be limited.

Prospecting hardware on the Moon, however, is an integral part of the framework. Prospecting/mining companies are among the only true customers of services during this phase. Secondary customers are companies performing risk-reduction and proof-of-concept experiments. For LunA-10, the specific use cases predominantly center around ISRU oxygen and robotic support operations.

The landers are the nexus of economic activity. This makes the largest barrier to entry and the largest economic opportunity: buying a ride to the Moon. The estimates for launch costs in the Exploration Age mirror current assumptions of $1M/kg.[13] With Starship (SpaceX) in early phases of flight test and Mk1 (Blue Origin) yet to achieve orbit,[14] launch cadence is limited during this time. While the launch and landing may be the primary service, landers provide additional critical services such as indigenous DTE communications services.[15]

While these DTE links are used for lander command and operation, they are also a data pipeline for payloads. Power for attached payloads is a major service from the lander; Starship has body-mounted solar panels, while the Mk1 in its node configuration is equipped with deployable panels. In the Exploration Age, wired power dominates, static facilities are plugged in, and rovers require either robotic assistance or are lifetime-limited by power.

14.3 The Foundational Age

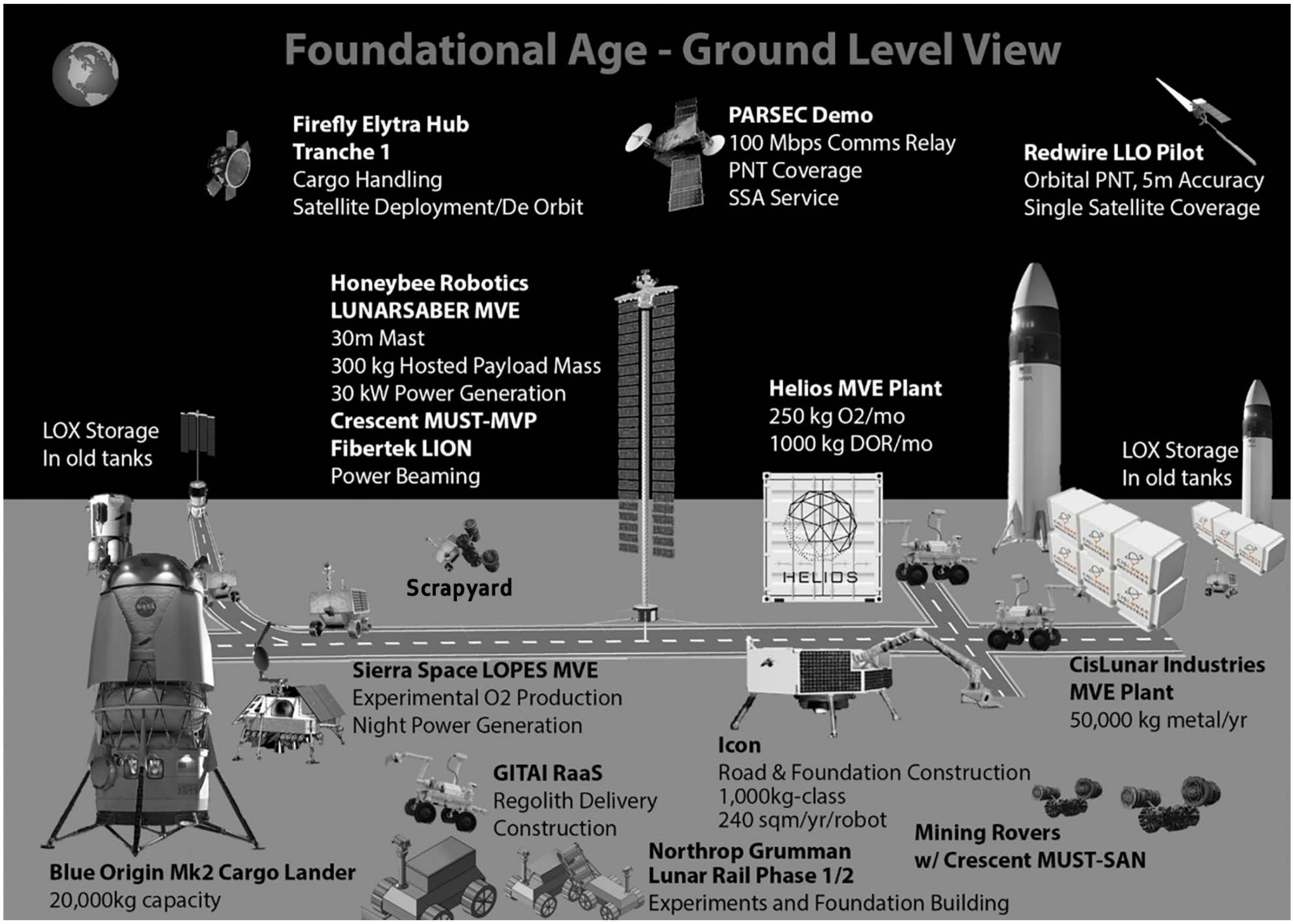


Figure 14.3. Hardware deployments during the Foundational Age

On the Moon, once the surveying activities of the Exploration Age have indicated promising areas for infrastructure, foundations can be built. The Foundational Age is defined as a transition period between early exploration missions and economically viable industrial activity. With existing landing sites and prospective mining sites requiring consistent traversing, the foundational infrastructure of roads, power, and communication lines can begin to be built. This development will lower the risk barrier to entry, enabling new economic players to enter the field. With these emerging players come new customers for infrastructure companies, starting an upswing in market demand. Now that services can be provided on a larger scale, peer-to-peer agreements may not be the most efficient way to transact, and early commodities markets begin to take form, selling services, raw materials, and finished materials.

One thing that is unlikely to change from the Exploration Age is the requirement to launch capital equipment from Earth. While landers may not drastically change in capability during this period, more launches are expected as the technology matures and demand rises. With existing power and communications infrastructure from previous landers and the start of multiservice towered hubs such as Honeybee Robotics' LunarSaber, cargo missions do not need to be as full-servicing and self-sufficient as before, leaving more accommodation for mission or monetizable cargo.

Towered hubs provide fort-like capabilities of the Exploration Age landers and can be deployed strategically, such as at the edges of permanently shadowed craters or mining areas away from landing zones. This drastically expands the viable area of operations. New commercial communications and local PNT architectures can link the various bases together, which will be useful for prospecting and mining applications. Whereas initial power generation methods were tested and deployed during the Exploration Age, experimental technologies developed in the Foundational Age take these advancements to the next level, conquering lunar night. One representative example is Sierra Space's LOPES ISRU plant. While able to generate its own power during the day, it also includes a fuel cell that can be recharged by electrolysis, provide power during the night, and even sell surplus power from the fuel cell to other users. Towered hubs can pivot to thermal hubs like LunarOasis. At first, this is merely outfitting a towered hub with a multilayer insulation (MLI) tent; when combined with more advanced thermal control systems, this can both take in heat from hot processes (ISRU plants, lasers) and redistribute that heat within the tent confines to keep equipment alive during lunar night. Customer equipment can now be designed without the mass, cost, and engineering burden of self-sufficient lunar night survival, a significant step change to the Exploration Age's state of the art.

In terms of capital equipment, technological advances during the Exploration Age have enabled experimental ISRU plants for production demonstration purposes. These can produce approximately 250 kg of oxygen per month, not enough to monetize but enough to act as a proof of concept, while also refining interoperable storage and transfer interfaces with other services. A metal recycling plant enters its initial experimental phase, building up to 50,000 kg/year of metallic throughput. Initial testing is accomplished with materials and in form factors (e.g., extrusions) of monetizable interest for future customers, such as rails for an eventual railroad, stock billets, and wire for remanufacture. Supply of recyclable materials will not be sufficient in the Foundational Age, so deoxygenated regolith or material brought from Earth may be used for experiments. While the Exploration Age landers may not be ready to be an input to the Re-ISRU process, expended fuel tanks on board may be repurposed for liquid oxygen storage, with robotic assets such as GITAI's Inchworm and Mover aiding in that deployment. This initializes a reduce, reuse, recycle ecosystem on the lunar surface.

The paths blazed by exploration rovers in the previous age lead to the trail-building portion of the Foundational Age, accomplished by a prototype laser vitreous multi-material transformation (VMX)–enabled construction system. Being able to build roads as one drives helps to build infrastructure while not interfering with adjacent lunar surface operations. Roads will be highly desirable in the burgeoning industrial developmental areas, namely mining areas and cargo transport areas (near landing pads and regolith processing sites). Depending on funding and vision of the investor community, early prep work for the lunar railroad may begin in the Foundational Age. This will heavily leverage the surveying done for road construction. The larger excavation-class rovers required for increased logistical operations also benefit from VMX-improved surfaces.

Orbital services begin to proliferate as well during this age. Firefly's Elytra-based Aggregation Hub, first deployed in GEO during the Exploration Age, will be brought into cislunar space, providing a transshipment point at EML1. In lower orbits, Crescent/Lockheed-Martin's Parsec and Redwire's orbital constellation begin to deploy. Although neither constellation will offer a full portfolio of services until the Industrial Age, these pilot missions serve to test hardware and establish a fledgling customer base. South polar coverage, 100 Mbps communications links, PNT ranging to 5-meter accuracy, and early synthetic aperture radar services may be available. During this time, additional satellites from both providers will gradually improve service.

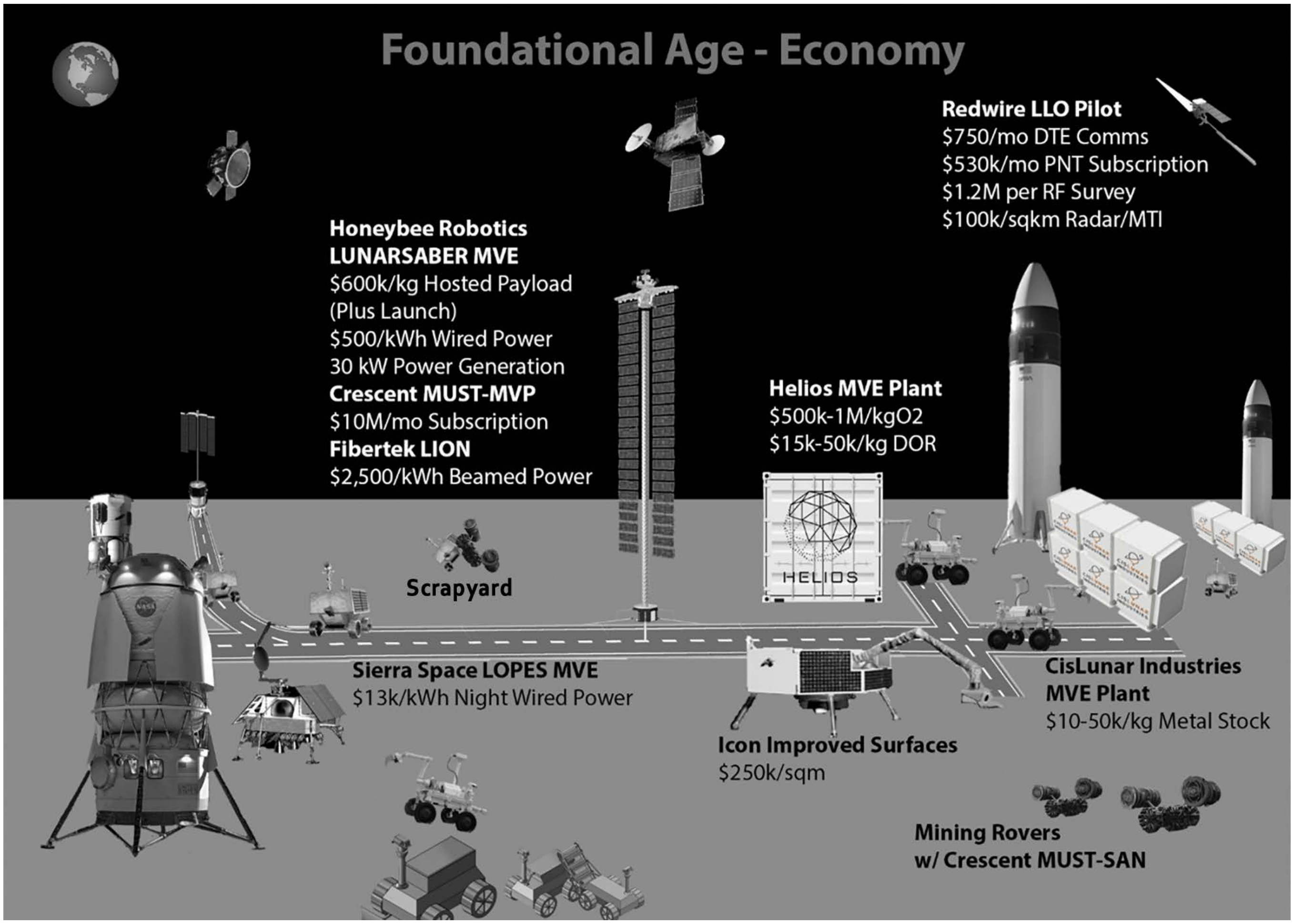


Figure 14.4. Costs of services during the Foundational Age

The economic landscape of the Foundational Age will have grown from the Exploration Age, but not to the level of self-sufficiency. As with the Exploration Age, launch costs are the main barrier to entry. Where landers once provided most of the basic infrastructure to their customers, now that landing areas are linked, more interoperable technologies exist. Remote, wire-based power delivery is still the primary method for static facilities like oxygen plants, but for mobile platforms, wireless power beaming is available from either landers or towered hubs, charged on a per-watt-hour basis.

With the increase in mobile assets for mining, road building, and hardware assembly, there will also be an increase in data demand and compute services. Additional data nodes for local area networks are deployed on various tall structures (e.g., Starship, Mk2, towered and thermal hubs such as LunarSaber and Lunar Oasis) as available. This increase in rover activity and density will increase demand and need for navigation accuracy. In addition to surface-based solutions, orbital services become available for a subscription service. Situational awareness and space traffic management data can also be subscribed to, from elevated towers or orbital surveys.

Using and enabling all these services, Robotics as a Service (RaaS) operates as hired labor, with a per-hour cost of $20–40k depending on platform, exclusive of communications costs. Construction services are in the building phase, charging $25k/m^2 for improved surfaces, whether they be facility foundations, landing pads, future lunar fixed base operators,[16] or roads.

14.4 The Industrial Age

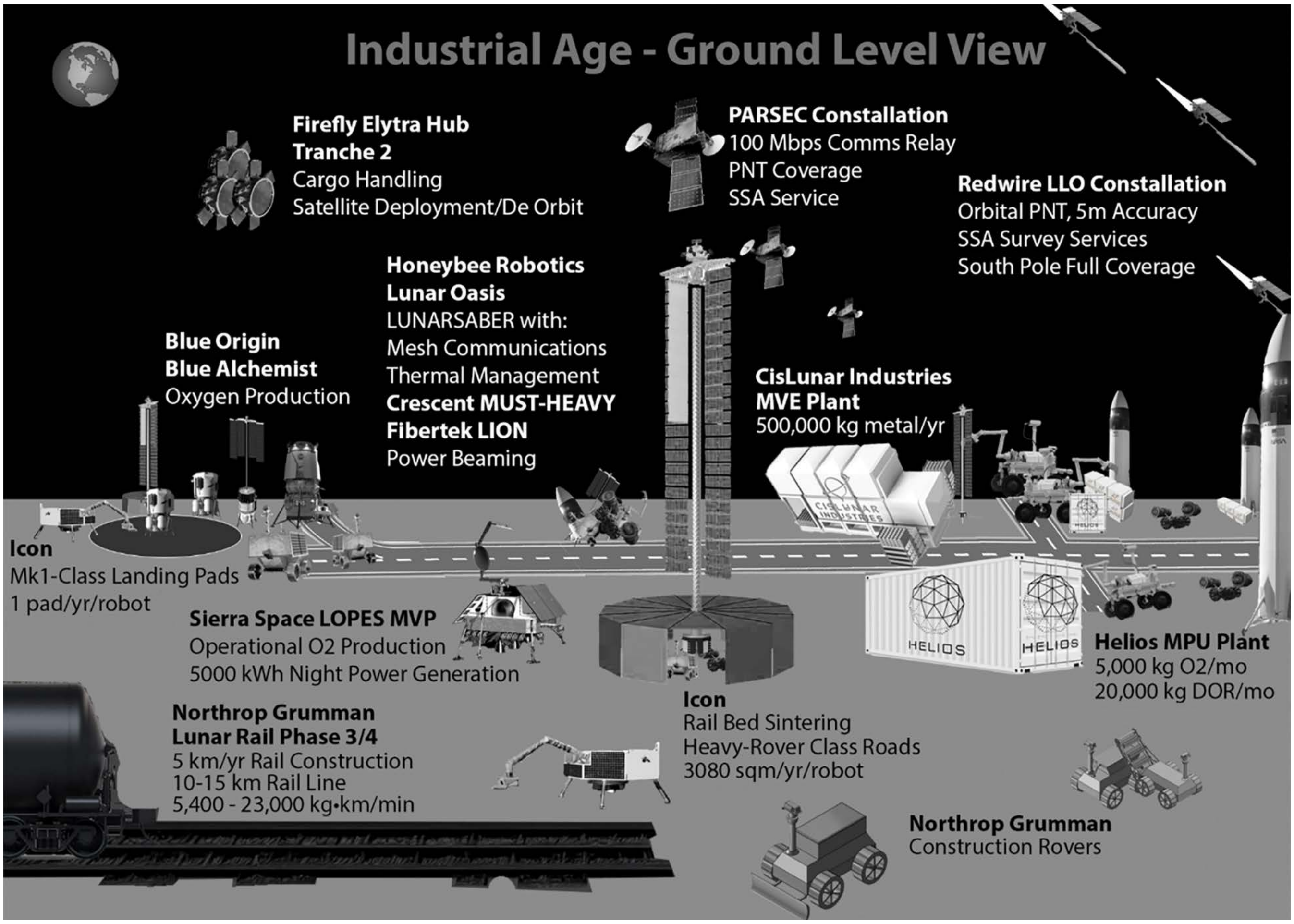


Figure 14.5. Hardware deployments during the Industrial Age

After the lunar surface has been explored and surveyed and foundations are built, industry can begin in earnest. Reduced launch costs, increased technical innovation, and improvements in infrastructure have enabled mining rovers to proliferate and carry larger mass payloads. Oxygen extraction plants continue to expand and increase throughput. Operational production facilities can now survive multiple lunar nights. And finally, the true sign of the arrival of the Industrial Age: cargo hauling along established routes reaches a critical mass that demands a more efficient surface transportation method.

As the Transcontinental Railroad brought a change from an agrarian economy to an industrial one, the lunar rail coincides with a transition from experimental lunar missions to profitable commercial lunar services and the beginning of the Industrial Age.

The main enabler of the Industrial Age is the lunar railroad. With increased cargo and mining operations centered in the same economic zone, more efficient means of transport are necessary. Large, excavation-class rovers introduced in the Foundational Age are now repurposed to build the rail and can be subsequently used for other mining or construction projects. The rail is built at a rate of 5 km/yr. At full operation, the lunar rail can carry 23,000 kg-km/minute, compared to 40 kg-km/min for Exploration Age rovers.[17] Additionally, larger-scale, reusable landing pads are built, accommodating an increased influx of heavy-lift landers. These landing pads reduce the risk of ejecta blast to nearby equipment and infrastructure and the uneven landing risk to cargo landers.[18] The pads also provide a platform to relaunch from, enabling large-scale rocket hop operations and the return of commercial lunar products to Earth. While the glamour of the early American Industrial Age centered around precious metals and gilded train cars, most economic returns came from sales of goods and services to the miners and laborers. Likewise, the infrastructure from the Foundational Age has grown in scale and is now providing returns. Given the ability to launch more hardware coupled with more efficient mining and processing, oxygen plants are finally at a scale where product can be sold on-demand. The full-scale Sierra Space and Helios plants combine to make over 100 tons/month of oxygen, with Helios also producing 480 tons/month of deoxygenated regolith to be circled back into manufacturing roads or extracting metals or used as raw material. The metal ecosystem from CisLunar Industries has grown production strength to 500 tons/year of metal of various types.

To power this activity, the towered hub network has expanded to multiple sites, increasing the operating area of the economic zone and the number of service customers. In addition, thermal hubs have been deployed, providing both night heat protection and day heat rejection as a service. This enables oxygen plants, sintering robots, power-beaming units, and other high-heat activities to distribute their heat more effectively and operate during lunar night at a more economically viable mass fraction.

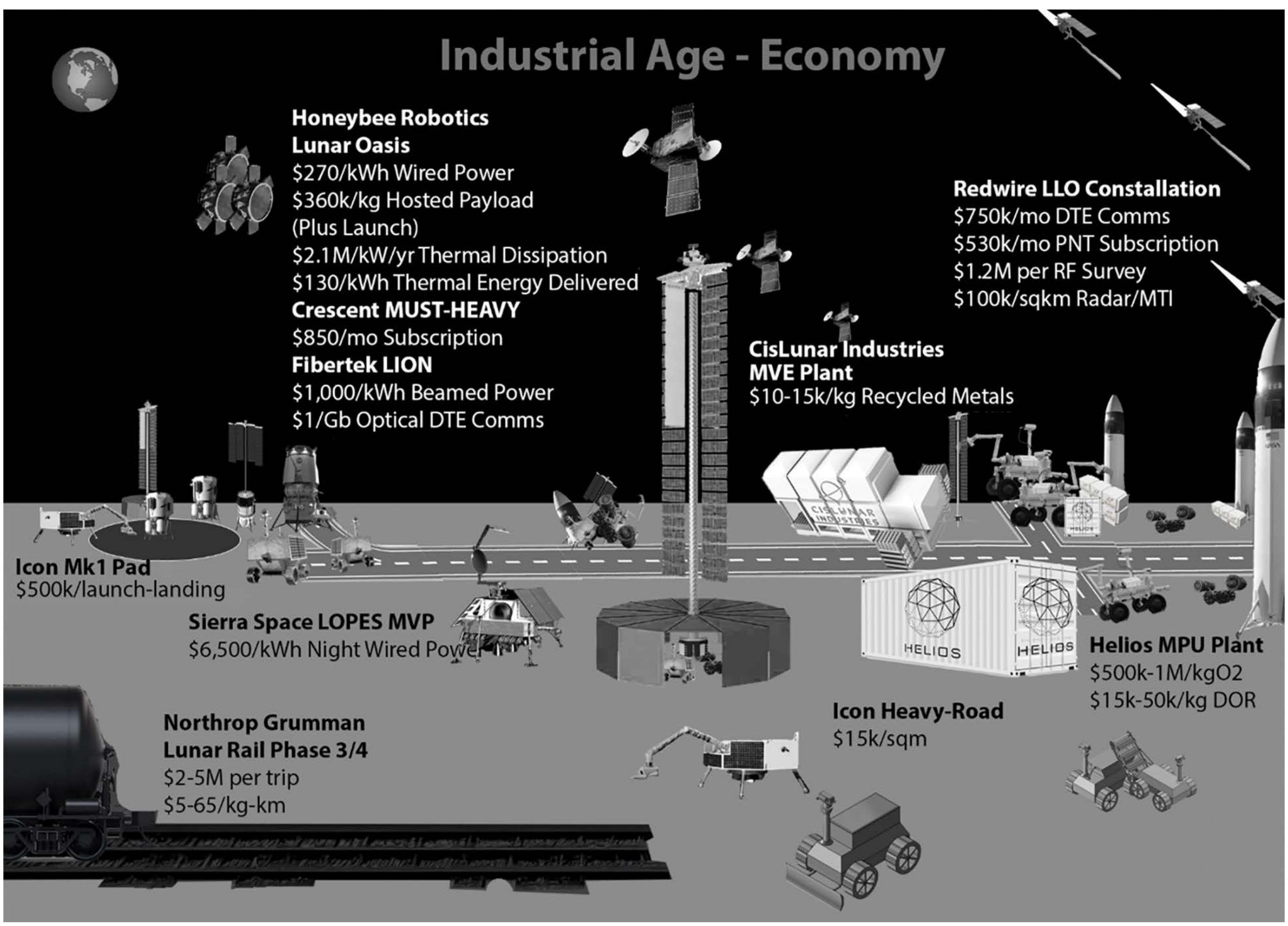


Figure 14.6. Cost of goods and services during the Industrial Age

As on the surface, orbital assets have also grown in size, mass, and scope. Full coverage in the south pole region for PNT, DTE communications relays, and space traffic management services are available. The cislunar aggregation hub has also expanded in size and overall capability.Now that services and production are at an industrial rate, a capital return on investment starts to manifest. Amortization of developmental costs for all infrastructure elements begins. The Industrial Age represents an era when technology development has matched with logistical capability and market demand to yield a productive economy. Once reaching the break-even point, further improvements in technology introduce new products and revenue streams, while increases in scale grow the established economic zone into new areas.

14.5 The Jet Age

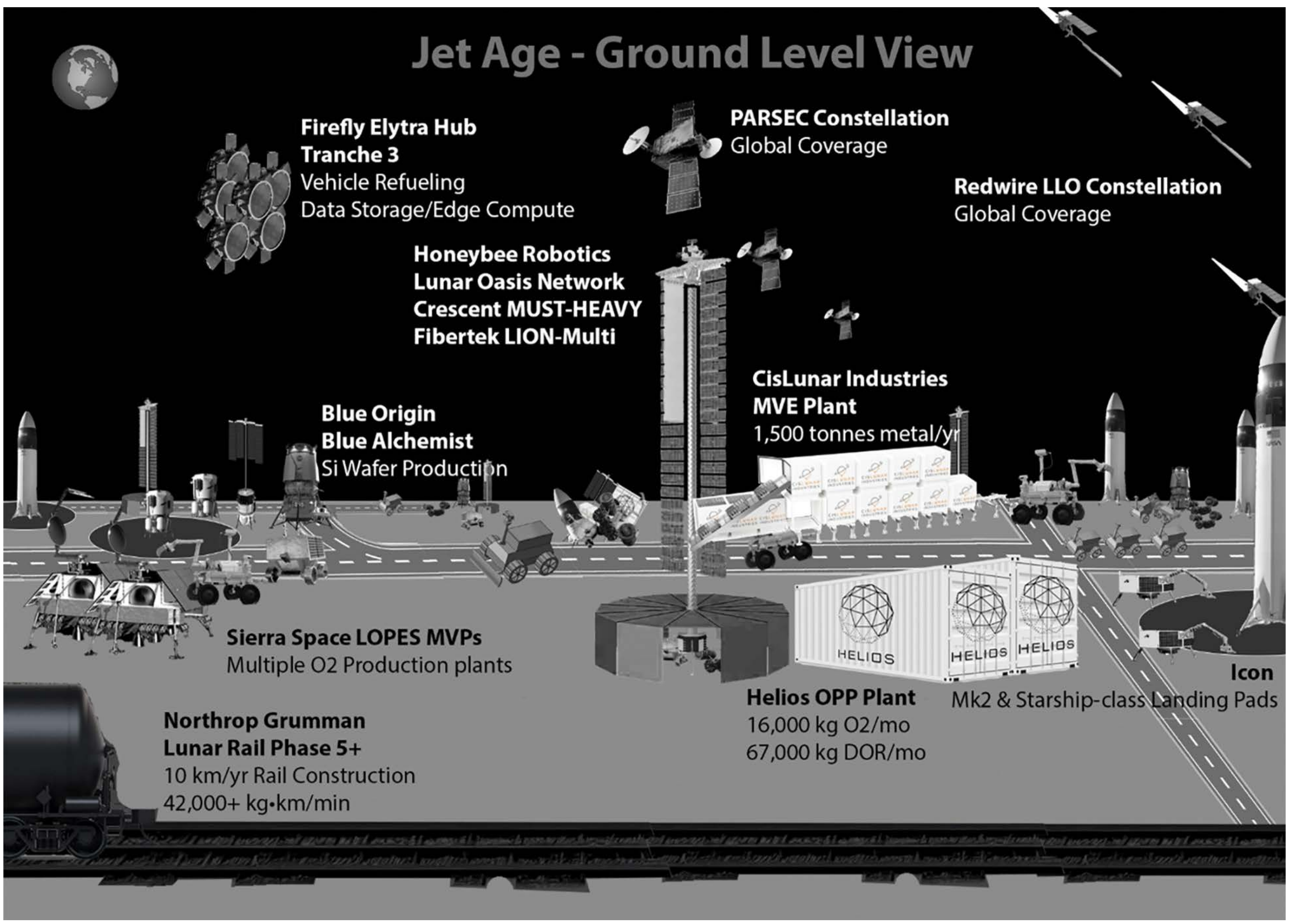


Figure 14.7. Hardware deployments during the Jet Age

The transition point from the Industrial Age to the Jet Age is when large-scale rocket hop transport can be accomplished with mostly ISRU materials. Rocket hop technology is currently in development and may be tested before the Jet Age. However, for rocket hops to be deployed at scale, a robust, full-coverage navigation, logistics, and space traffic management infrastructure needs to be built.

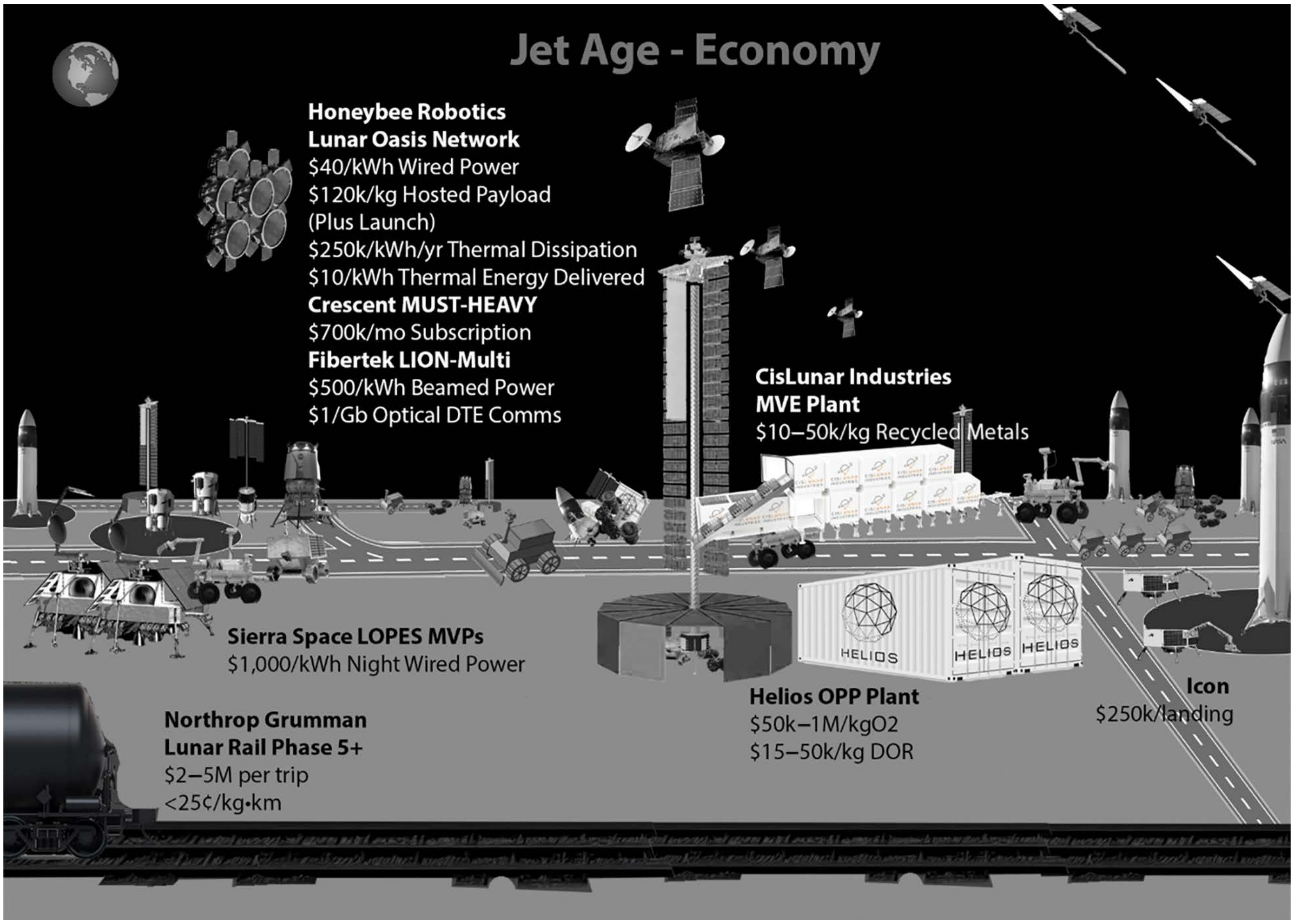


Figure 14.8. Costs of goods and services during the Jet Age

As overall launch-from-Earth costs come down, the ability to refuel hoppers with cheaper, ISRU fuel becomes economically advantageous. In the case of Starship, 100,000 kg of fuel is required for many mass-mobility trajectories. This requires 50,000 kg of oxygen in situ for each flight, augmented by methane brought from Earth, at a cadence that meets a one-flight-per-month demand.

Now that all areas of the Moon can be covered, more expansive communications, navigation, and situational awareness are required. Orbital constellations providing full lunar coverage become important. The cislunar logistics hub begins to accommodate increased cargo traffic and provide edge computing for commodities markets,[19] all enabled by large-scale ISRU fuel production.

14.6 Conclusions

Designing a self-sustaining lunar economy in a ten-year time frame, especially when no infrastructure exists today, is a "DARPA-hard" tall order. Perhaps the most valuable takeaway from the frameworks is to see, in a quantifiable and scalable manner, what is necessary from a funding, engineering, and technology development perspective for this vision to come to reality.

Early subscription costs for services such as communications and PNT, especially in the Exploration and Foundational ages, are expected to be high due to the cost to get the hardware to the Moon. This limits early missions. As the cost barrier lowers, the risk of doing business lowers to a reasonable level, companies begin to see a return on investments, and the lunar economy can grow to a level of self-sustainment. From a technical point of view, the largest driver affecting the proliferation of activity on the Moon is accessibility to launch. Early standardization and collaboration are likely to emerge as the keys to forming a cooperative, interoperable, and international economy. This finding has driven the DARPA establishment of the LOGIC standards consortium, discussed in chapter 22.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. United States Geological Survey.
2. Authors Britton and Stohlman are from NASA Langley Research Center.
3. US Air Force Academy and US Space Command.
4. United States Air Force, 8th Special Operations Squadron (AFSOC).
5. United States Space Force, 19th Space Defense Squadron.
6. Authors Boyd and Daniels are from United States Space Force, 2nd Space Operations Squadron.
7. Authors Batjer and Pele are from Blue Sky Innovators (in support of Defense Advanced Research Projects Agency, DARPA).
8. Mach 20 (in support of DARPA).
9. DARPA.
10. Mendell et al., *Lunar Bases and Space Activities of the 21st Century*.
11. As of August 2024.
12. "Principles of the Mineral Resource Classification System of the U.S. Bureau of Mines and the U.S. Geological Survey," US Geological Survey, 1976, https://doi.org/10.3133/b1450A.
13. Commercial estimate (Astrobotic Inc.) for payload to the surface of the Moon, current as of May 2024.
14. As of August 2024.
15. For example, Blue Origin Mk1 lander uses an RF-based system; SpaceX Starship uses an optical connection to its Earth-based Starlink network.
16. FBO: Fixed base operator. At terrestrial airports, FBOs provide aeronautical services such as refueling, hangaring, maintenance, instruction, and parking.
17. Analysis based on proposed HL-MAPP rover from Lunar Outpost, data from May 2024.
18. For example, Intuitive Machines' first lander mission, IM-1 (Odysseus lander), landed on a 12-degree slope, skidded along the surface of the Moon, broke one of its six legs, and tipped over onto its side. Kenneth Chang, "Moon Lander Is Lying on Its Side but Still Functional, Officials Say," *New York Times*, February 23, 2024, https://www.nytimes.com/.
19. Discussed further in chapter 17.

15

Lunar Economy Value Chains

Edited by Michael Nayak[1]

Contributing authors: Shawn Britton, Olive Stohlman,[2] Elizabeth Hyde,[3] Luke Sauter,[4] Daniel Kulp,[5] Katelyn Eppich,[6] Curtis Boyd, Joshua Daniels,[7] Ashley Batjer, Lee Pele,[8] Christine White,[9] and Michael Nayak.

15.1 Introduction to Value Chains

As outlined in chapter 14, the LunA-10 frameworks describe how individual technology-based systems and components may interact in demands, services, product volume, and costs. It is imperative that the technological "puzzle pieces" on the lunar surface fit together well and are of the relatively same size.

While the frameworks show a technically feasible picture of what the lunar economy can look like, we need to show *how we get there.* To address this, LunA-10 examined how multiple, seemingly disparate operations would interface from a task perspective to create commercial services. This examination included how operations and activities might change in maturity and complexity across the LunA-10 decade. With the ultimate guiding principle of sustainable commercialization, a tool typically used for economic development was used to detail these interactions: value chains.

Developed in the 1980s by economist Michael Porter,[10] value chains lay out the series of consecutive steps and feedback loops that go into creating a product, from inception to completion. Value chains are routinely used as an insight tool for terrestrial economic and industrial market productivity analysis.[11] Value chains have also been applied to the space sector.[12] In situ resource utilization (ISRU) has established examples of value chains analogous to their use in terrestrial mining.[13]

When applied to the technology development framework of LunA-10 (chapter 14), value chains serve as a supplemental framework for identifying the maturity to perform a given operation, either with today's state of the art or as a technology development forecast. Conversely, it also identifies where additional technical focus may be necessary.

15.2 The LunA-10 Value Chain Construct

Lunar surface operations were arbitrarily divided (fig. 15.1) into five functional areas: (1) transportation and logistics; (2) communications; (3) positioning, navigation, and timing (PNT); (4) power; and (5) ISRU. Certain cross-cutting operations and functional capabilities, such as enabling robotics and construction operations, were considered inherently integrated into other value chains and not included as separate analysis threads.

For each functional area, common operation elements were determined: universal enough to apply to any use case but sufficiently granular to detail the process. These overarching functional chains were codified as *enterprise value chains*—capable of being carried as a common framework across multiple use cases and developmental timeframes yet enabling relative comparison of technical maturity.

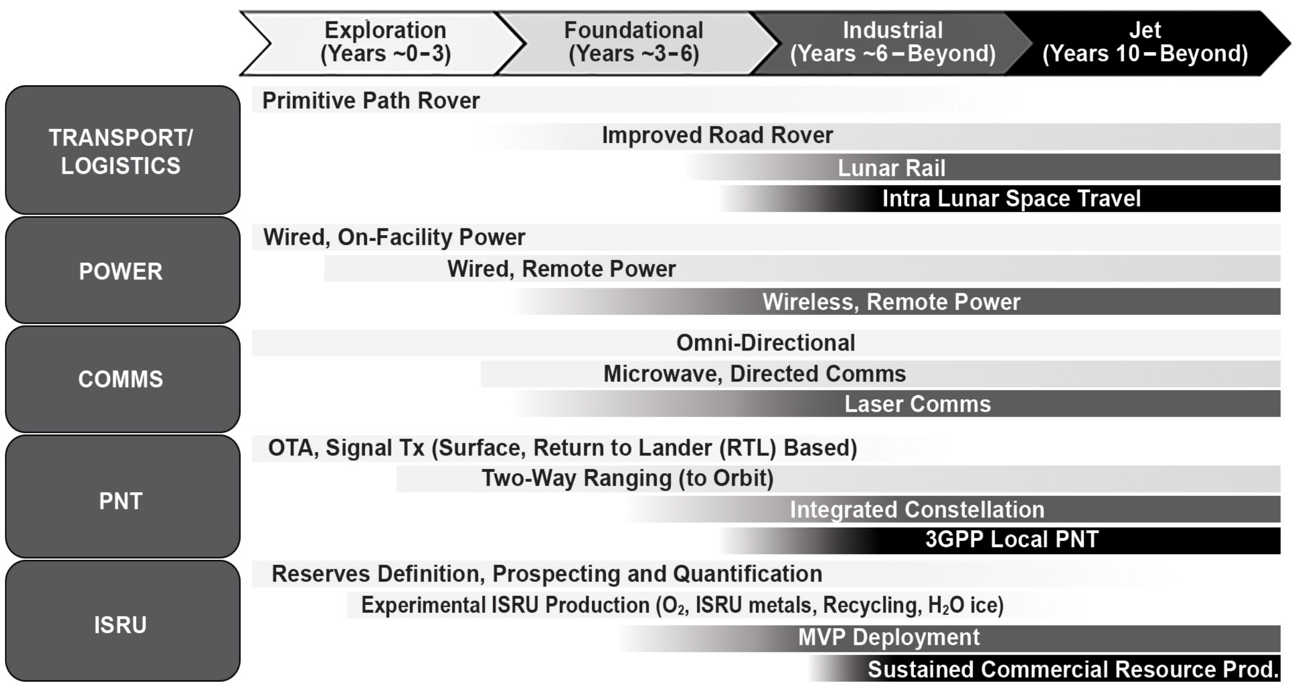
Use cases were identified using a "crawl, walk, run" approach to technical development. These spatially demonstrate demand as the lunar surface ecosystem spreads and aid in understanding temporal changes and specific intent. These are referred to as *discrete-level value chains*.

With enterprise and discrete-level value chains defined, a second-order analysis is performed for specific tasks and functions required to accomplish each operation. These tasks indicate the technical maturity and the associated degree of difficulty in fulfilling each functional element on the lunar surface.

Section 15.4 provides a detailed walkthrough of two discrete-level value chains from a single functional area to explain the process and benefits of value chain application. In total, seventy-one value chains were charted during LunA-10; only a fraction of those are presented in this chapter.

15.3 LunA-10 Timeline of Value Chains

A "crawl, walk, run" approach allows the alignment of discrete use cases with the phases outlined in chapter 14. As highlighted in figure 15.1, some cases will emerge in prominence as the technology matures, allowing other operations to decline in usage. For example, return to lander (RTN)–based PNT will likely fade as integrated constellation PNT becomes prevalent. Some capabilities will remain consistently needed, such as on-lander wired power and omnidirectional communications.



Key
ISRU: in situ resource utilization
MVP: minimum viable product
PNT: positioning, navigation, timing

Figure 15.1 Forecasted value chain use case predominancy across the LunA-10 decade

In this chapter, the transport and logistics functional area (fig. 15.1) serves as a representative example to illustrate how a value chain is generated. This area begins with a *Primitive Path Rover*, a simple, less than 200 kg rover on an unimproved surface, where there is minimal knowledge of predetermined paths.[14] As the Foundational Age begins, this transitions to larger, commerce-sized transport and construction rovers. These *Improved Road Rovers* use common routes and benefit from a prepared transit surface. As the Industrial Age and large-scale cross-mass begin, predominant commodity routes become the basis for lunar rail construction. Finally, as the lunar surface becomes a widespread network of settlements with orbital stations providing support, intra-lunar rocket travel becomes prevalent, aided by technology improvements in landing pads and fueling infrastructure.

A similar narrative can be established for the remaining four functional areas; these describe how temporal technological advances dictate the predominant capabilities employed in the lunar ecosystem. This forecasting ensures critical path capabilities are established to support the greater functional need.

A walkthrough of the process for two specific use cases within the transport/logistics functional area is provided next. A similar development process was followed for all seventy-one value chains analyzed.

15.4 Representative Example: Transportation/Logistics Functional Area

15.4.1 Operational Gates in Enterprise Value Chains

An enterprise value chain provides common analysis of each use case in a functional area, representing all activities that lead to a product. For the transportation/logistics functional area, this product is the delivery of a payload to a location on the surface.

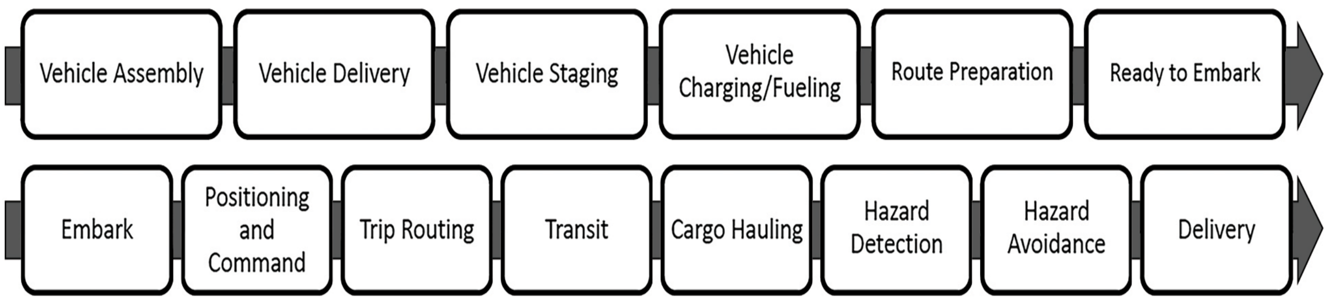


Figure 15.2. Transport/logistics enterprise value chain, with operational gates highlighted

For a functional area, as illustrated in figure 15.2, natural operational gates serve as useful delineators in the execution process. These (1) identify common complexities where activities are similar across multiple use cases, (2) identify opportunities for standardization, and (3) serve as foundations to establish normative taxonomies across use cases. For example, in the functional area of power, value chains can be delineated between provider services and receiver services, with transmission as the delineator. For transportation, delineators exist between pre/post transit (embarkation) and under-transit activities.

15.4.2 Use Case Value Chains

With enterprise value chains specified, specific use cases are applied next, to examine technologies associated with each element and their level of maturity. This helped establish how one commercial entity's capabilities can interact from an operational level to support other entities. Using the specific examples of LunA-10 consortium companies, figures 15.3 to 15.6 indicate which commercial entities have technical capabilities for a given element of the value chain and what those entail for progression from a primitive path rover to lunar rail operation. For the lunar rail case, a network of prepared routes was developed based on likely commodity needs of the Industrial Age.

A notional evaluation of technological maturity can then be undertaken. Elements with comprehensive technical capability discussed within this *Field Guide*, or analyzed within the LunA-10 program, are coded in darker shades. Elements where some technical capability exists within LunA-10—but additional technological development is necessary—are indicated by lighter shades.[15]

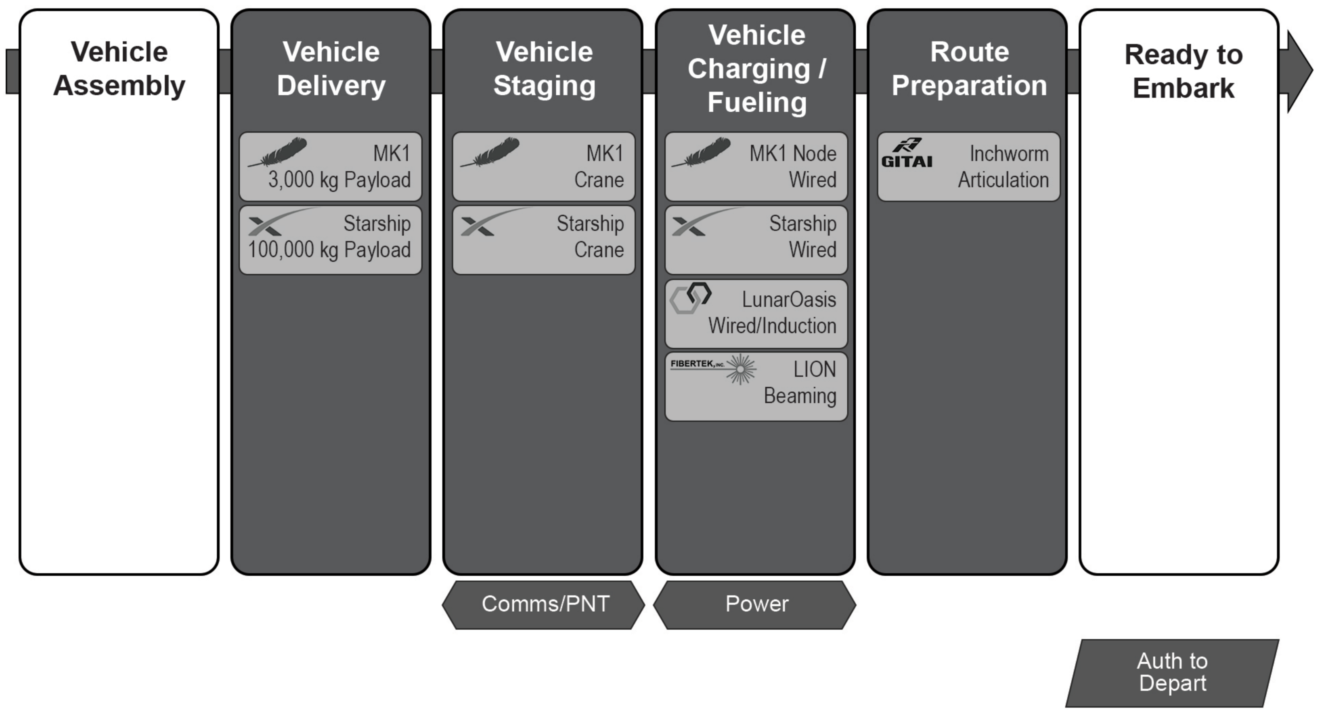


Figure 15.3. Primitive Path Rover, performer alignment, prior to embarking (pre-underway) phase

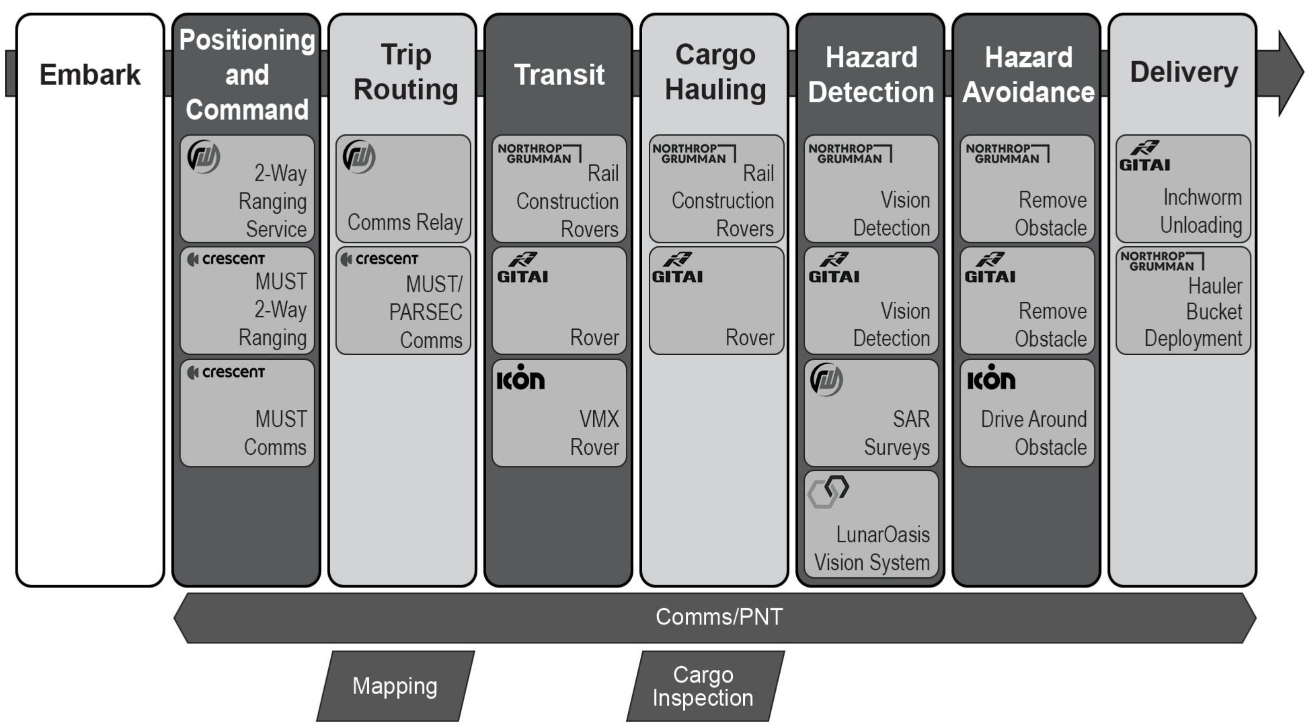


Figure 15.4. Primitive path rover, performer alignment, underway phase

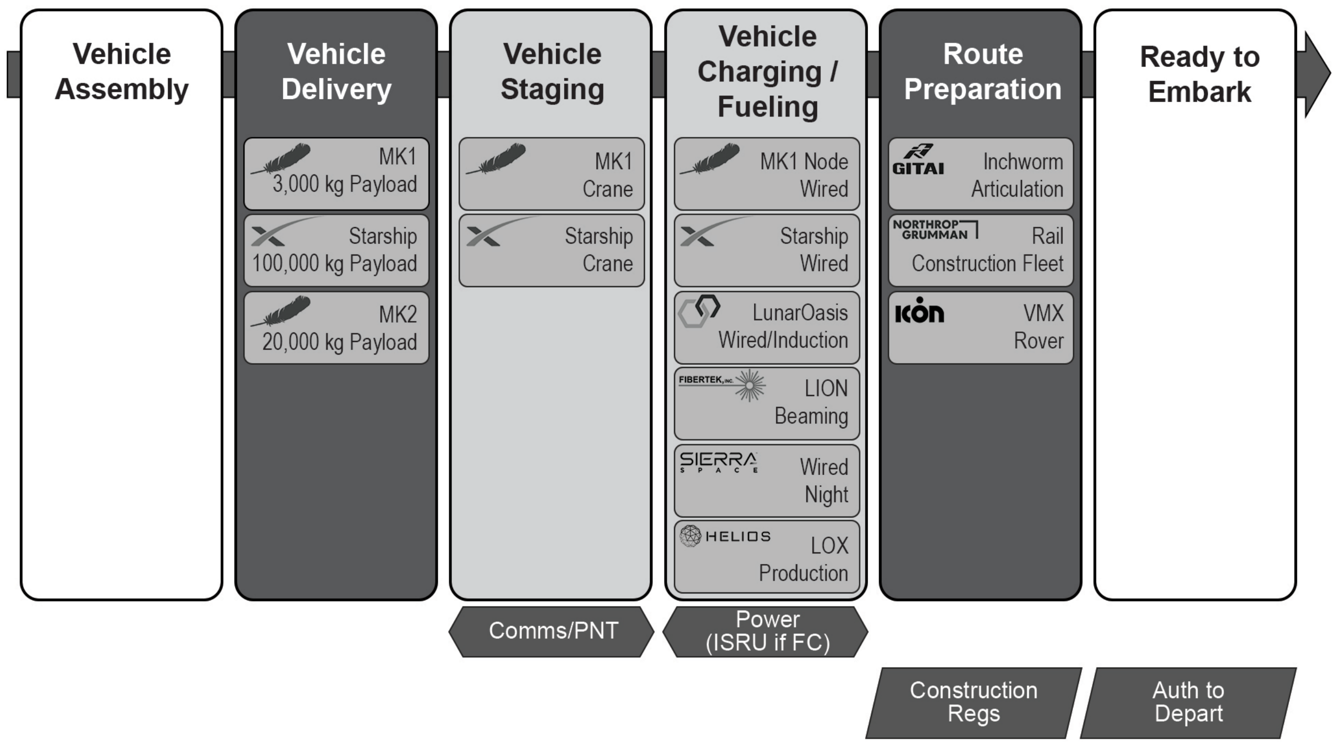


Figure 15.5. Lunar rail transport, performer alignment, prior to embarking (pre-underway) phase.

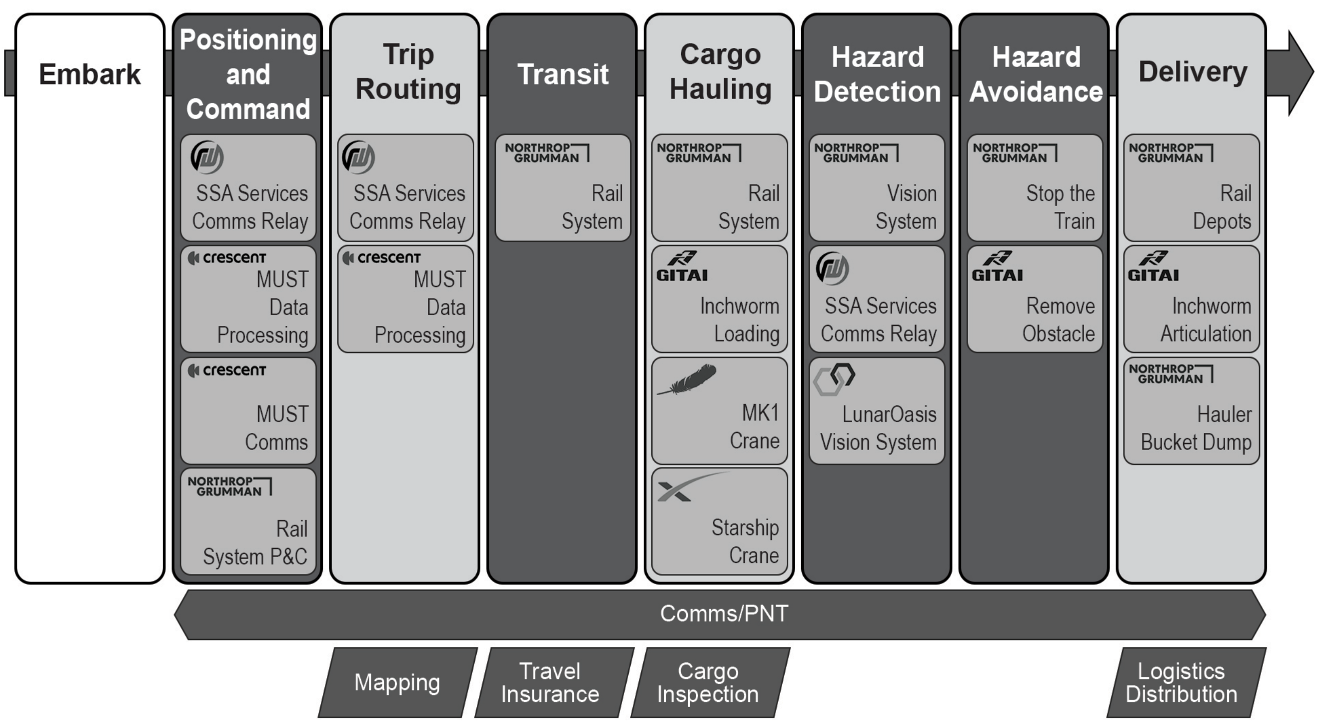


Figure 15.6. Lunar rail transport, performer alignment, task analysis detail, underway phase.

It is of note that no single company has full execution of any value chain. Partnership and interaction with other systems and performers is not just desired for operational success and a sustainable lunar economy, but required.

15.4.3 Value Chain Connections

The inherent complexity of lunar operations necessitates a network of adjacent operations. When a certain element of a value chain will rely on an adjacent value chain for capability, it is indicated by a hexagonal icon.

Other nontechnological support areas are essential to effective lunar operations. Referred to as *enabler perspectives a*nd partially discussed in part 3 of this *Field Guide*, these include legal, regulatory, insurance, inspection, security, dispute adjudication, and many more. While it is overly speculative to explore each of these in the value chain methodology, some foreseen needs and integration points are highlighted by rhombi below a given element (for example, in fig. 15.7).

15.4.4 Second-Order Task Analysis

For each value chain, a second-order analysis was performed to dive into the specifics of technical activities necessary for a use case (fig. 15.7) and provide insight into degrees of complexity for a functional element. It also indicates where tasking may be common across multiple use cases, signifying opportunities for standardization of services. Lunar interoperability is discussed further in chapter 22.

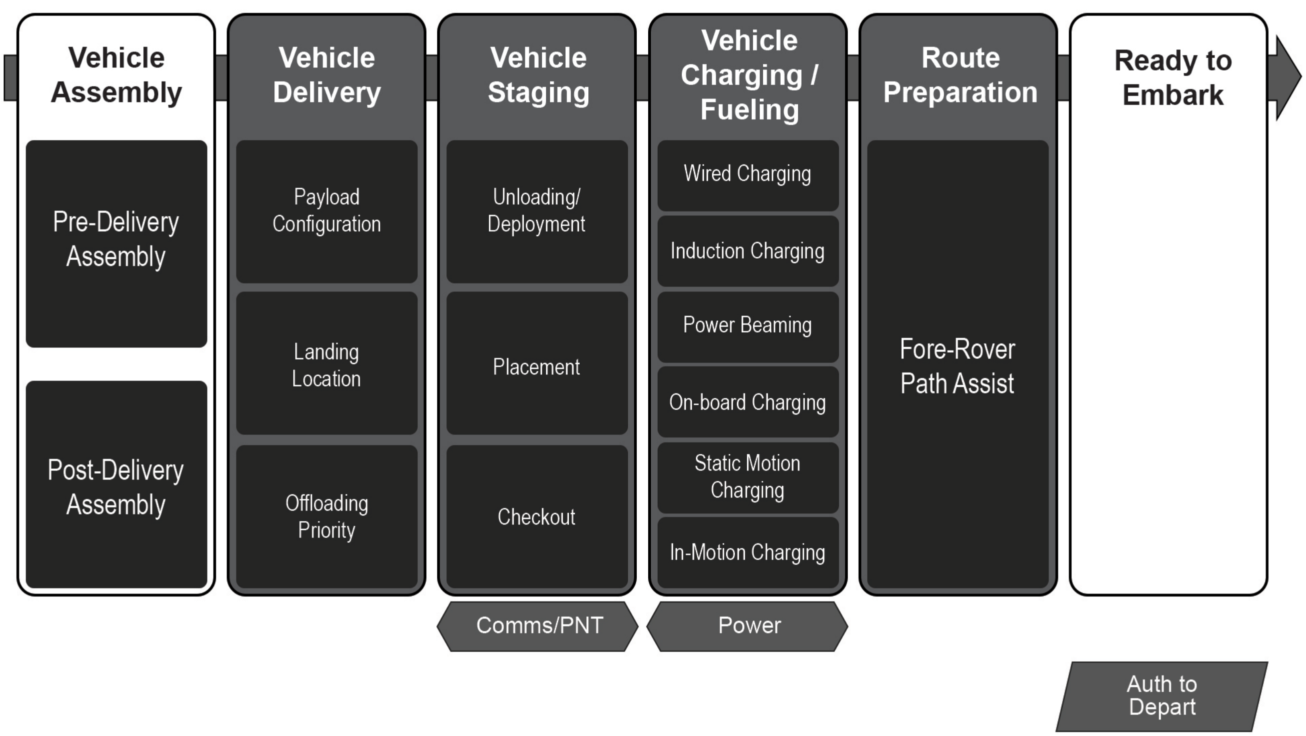


Figure 15.7. Primitive path rover, task analysis detail, prior to embarking (pre-underway) phase

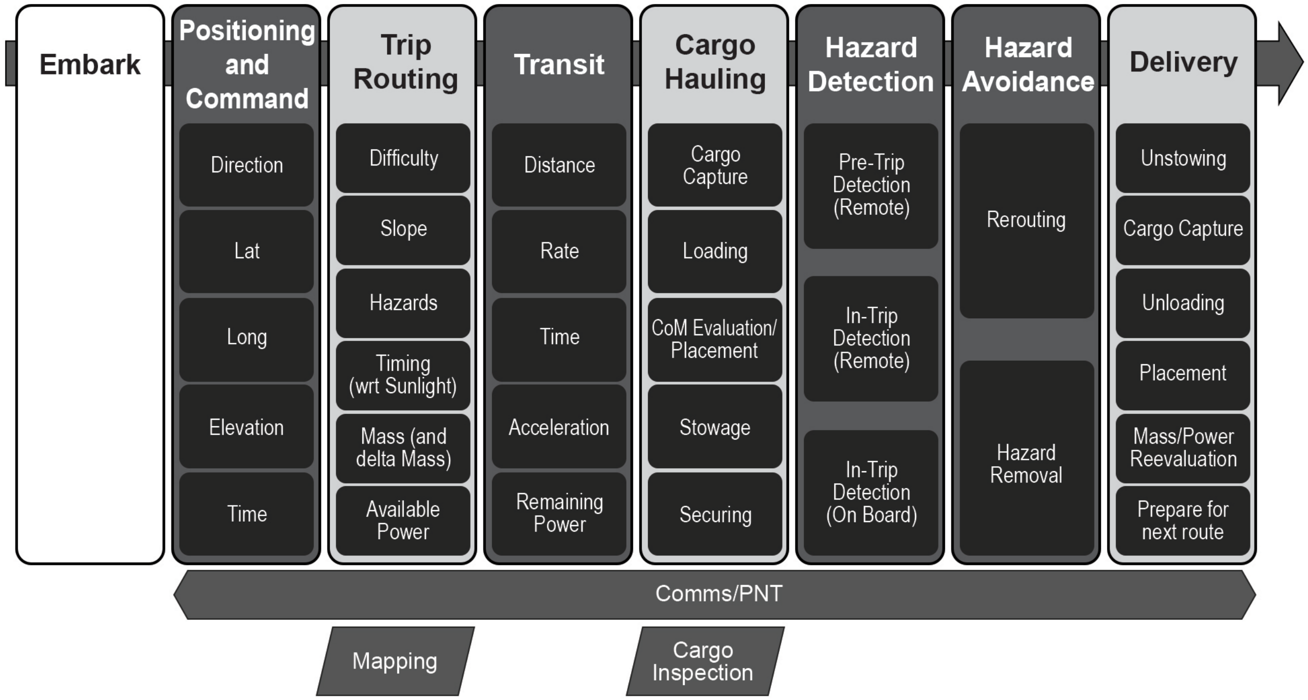


Figure 15.8. Primitive path rover, task analysis detail, underway phase

Cross connections to other value chains and enabler perspectives are shown beneath value chain elements. For the Primitive Path Rover, enabler perspectives are limited due to the frontier nature of the economy. As the economy matures through the Foundational and Industrial ages, enabler connections begin to grow.

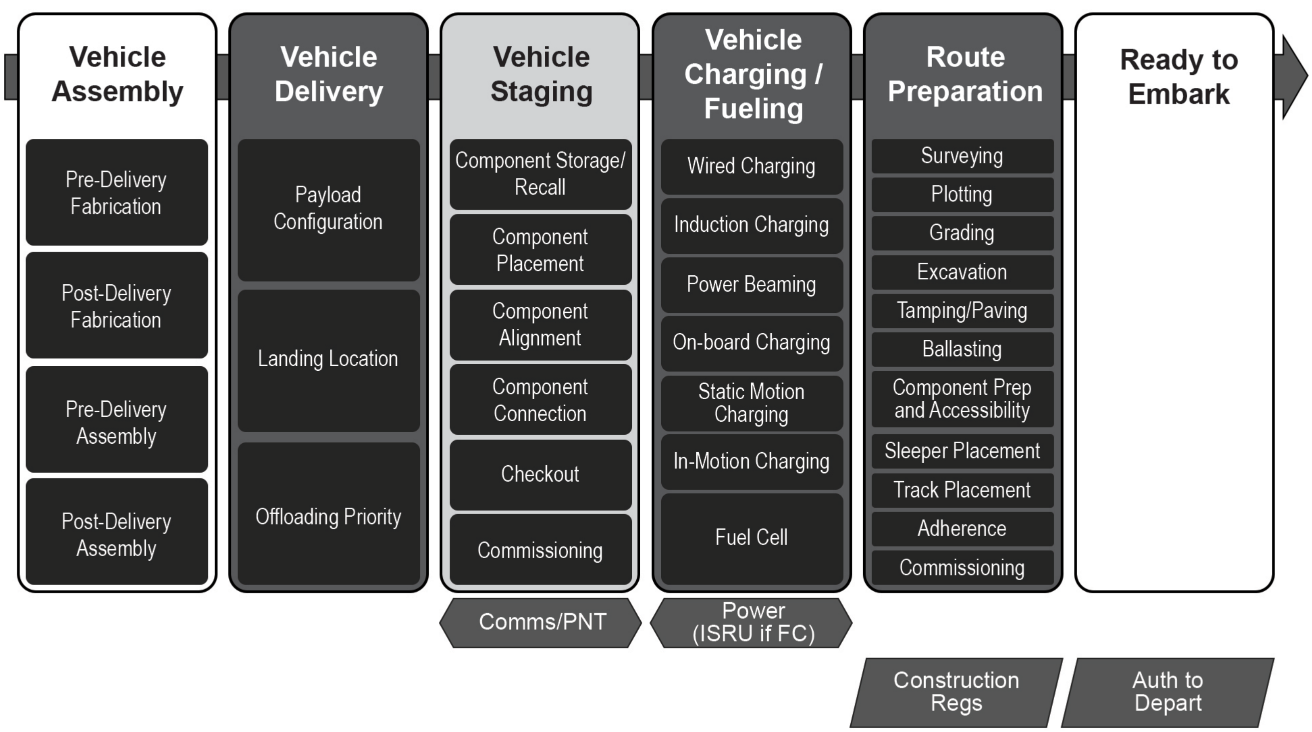


Figure 15.9. Lunar rail transport, task analysis detail, prior to embarking (pre-underway) phase

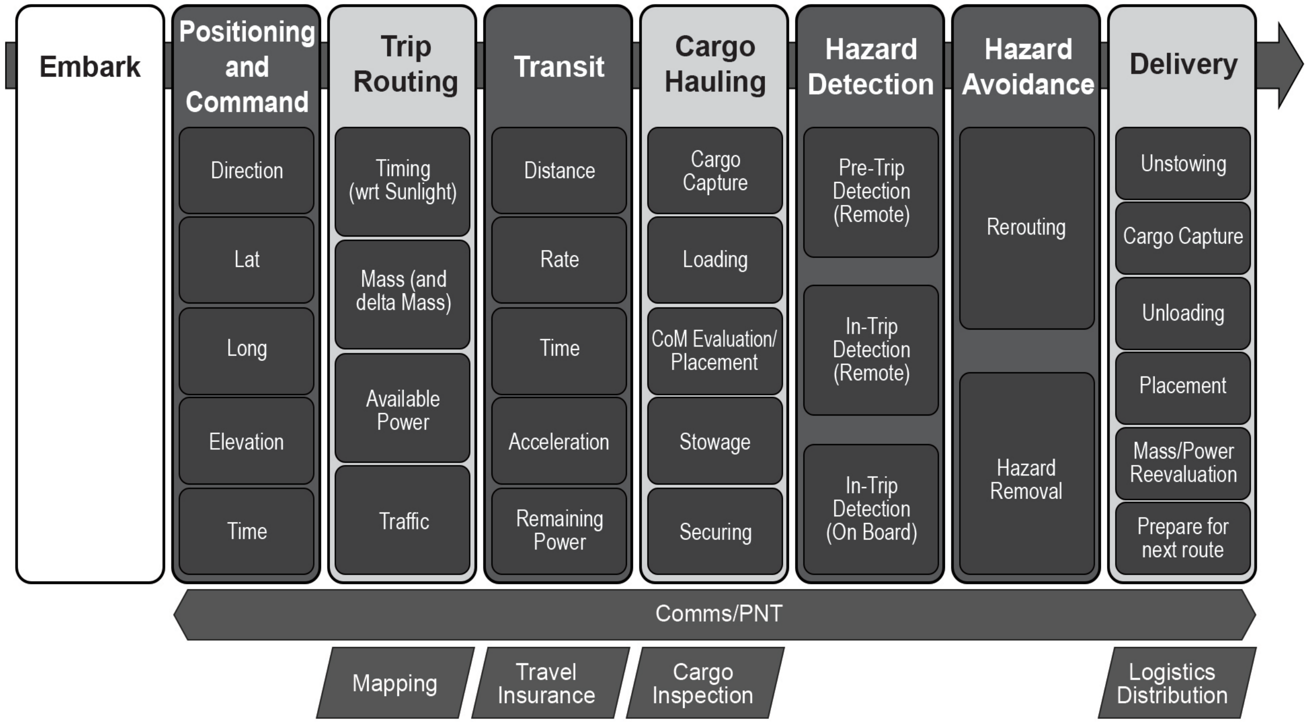


Figure 15.10. Lunar rail transport, task analysis detail, task analysis detail, underway phase

To demonstrate the evolution of technical complexity across different use cases, a comparison between "route preparation" tasks for a Primitive Path Rover and lunar rail is provided in figure 15.11. This provides the significant preparation necessary to enable advanced technology goals at the end of any enterprise value chain (here: lunar rail transport). It also highlights areas where additional technical development is necessary or where terrestrial capabilities may be extrapolated for lunar use.

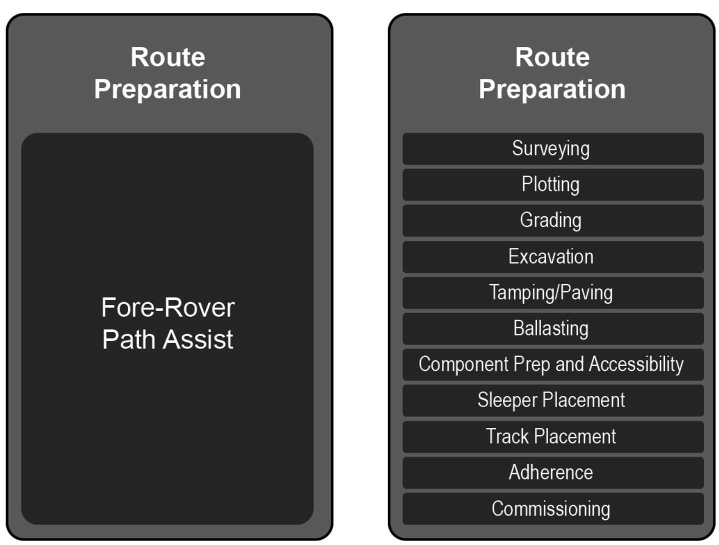


Figure 15.11. Task complexity comparison, route preparation element: Primitive path rover (left) vs. lunar rail use cases (right)

Future analysis, when baselined in existing or currently funded technology, could deconstruct each task into a third-order level of detail. This level of detail can integrate directly with operational systems engineering approaches.[16]

15.5 Conclusions

The overall intent of developing lunar value chains was to create an extensible, flexible construct that establishes technical areas, determines future investment paths, and plans future development. Additional functional areas and respective enterprise constructs can be created by the greater lunar community to expand the value network, such as through consortiums like DARPA's Lunar Operating Guidelines for Infrastructure Consortium (LOGIC, chapter 22) and NASA's Lunar Surface Innovation Consortium (LSIC).

The two use-case–level value chains illustrated in this chapter serve as one example of a larger framework set compiled under LunA-10. Interactivity between value chain operations creates a "value network" of mutual influence on availability and capability. Without these cross-connections, an effective, self-sustaining lunar economy is not viable. Future work is planned to use graphical user interfaces to develop 3D mappings of this value network.

Technology developers and lunar architects can use this construct to effectively identify where specific capabilities can integrate and mature well-defined interfaces and product transfers. From a business perspective, the construct assesses the needs and demand signal for products under development. It can also identify areas of high value growth, where additional development can unlock large capability jumps.

In addition to identifying infusion points within the existing operational frameworks, enabling perspectives also drive supplemental value chains that lay out actions necessary for execution, especially as the value network matures.

These enabling perspectives and their impact on the lunar economy are discussed in part 3 of this *Field Guide*.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Defense Advanced Research Projects Agency (DARPA).
2. Authors Britton and Stohlman are from NASA Langley Research Center.
3. United States Geological Survey.
4. US Air Force Academy and US Space Command.
5. United States Air Force, 8th Special Operations Squadron (AFSOC).
6. United States Space Force, 19th Space Defense Squadron.
7. Authors Boyd and Daniels are from United States Space Force, 2nd Space Operations Squadron.
8. Authors Batjer and Pele are from Blue Sky Innovators (in support of DARPA).
9. Mach 20 (in support of DARPA).
10. Porter, *Competitive Advantage*.
11. Kaplinsky and Morris, "Handbook for Value Chain Research."
12. Luxembourg Space Agency, "Opportunities For Space Resources Utilization"; and European Space Agency, "Low Earth Orbit Value Chain."
13. See, for example, Sanders et al., "Lunar Mining and Processing"; and Gorner et al., "The Mine-to-Market Value Chain."
14. For example, NASA's Volatiles Investigating Polar Exploration Rover (VIPER).
15. In some cases, the technical capability may exist but was not developed to a system concept review (SCR) level of detail.
16. Hassan, "Engineering Supply Chains as Systems."

PART 3

BEYOND THE TECHNOLOGY: ENABLING PERSPECTIVES

16

Economic Enablers and Inhibiters from Space Treaties and International Law

Charles (Chase) Hamilton[1] *and James N. Head*[2]

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16.1 Legal Underpinnings of the Lunar Economy

A key element of any architecture development activity is identification of architectural drivers.[3] Just as vital as the technical constraints, economic or business constraints will influence the commercial lunar architecture and are examined in this chapter.

International access to and participation in the lunar economy provides benefits ranging from burden sharing and market access to international legitimacy. Therefore, we consider the economic constraints and interests of stakeholders through the lens of existing international treaty and customary international law (CIL). Interpretations of treaties and CIL provide the framework for the rules-based order necessary for a thriving lunar economy. Ideally these will provide the predictable legal and policy environment that investors require and enable enforceable protections of legal rights for commercial lunar development. However, controversial legal questions, including about property, remain unresolved in ways that may impact the LunA-10 vision. This chapter analyzes how the legal framework pertains to the technologies and implementations presented in this book. With respect to each, we will consider whether and how new legal developments must emerge.

Power systems (chapter 4) need assured long-term protection of surface infrastructure as well as easement rights for power lines, to the extent they run over another's property. Wired power will face many challenges familiar to terrestrial users—vulnerability to excavation, vehicle collisions—but also new factors such as space weather events. If wireless transmission is used, the power system must avoid harmful interference with other systems, potentially at both optical and radio frequencies. Likewise, wireless systems must be protected from dust generation affecting the provider and user. In addition, a legal rules-based regime must contemplate the consequences of off-nominal power transmission. The regime will need to determine rights to possession and use, control, and exclusion of both real property (the land and attached structures) and personal property (equipment, machinery, etc.), with a set of rules establishing liability and private, national, and international responsibility.

Mining activities (chapter 5) require a recognized and enforced regime with rights to extract, refine, use, and sell or transfer the materials. In addition, mining operations often involve considerable planning, investment, and protection of access to the ore body, to the potential exclusion of others. To the extent actors should be permitted to maintain rights of exclusion before and during a mining operation and during any hiatus due to market conditions rendering extraction unprofitable or infeasible, this may imply a need for long-term exclusive access to certain sites on the Moon. The mining organization will also require long-term access to supporting infrastructure such as power, roads, and rail. Mining operations themselves can cause harmful interference, such as through dust generation.

Metal recycling (chapter 6) will involve many of the same considerations as mining, with an additional complication. Disputes may arise around the rights and limitations regarding the inputs for recycling. For example, a functioning metal recycling enterprise will provide a market for expended space vehicles, potentially including legacy vehicles such as those found at Apollo landing sites. Some of these vehicles and sites are of great historic interest, raising questions about their protection. Further, the Apollo and Chang'e sites contain radioactive power sources, which increase the risk of harmful contamination if salvage operators collect the material without knowing the radioactive material exists or having the technical competence to handle the material safely. Finally, actors may contest the ownership of abandoned, expended, and partially functional items, inviting a legal system that clarifies salvage rights on the Moon.

Communications and positioning, navigation, and timing (chapter 7) will have many transmission interference and infrastructure concerns in common with power beaming. Spectrum management on the Moon is an area of active consideration at the International Telecommunications Union, which has established an Interagency Operations Group. At present this appears the area most likely to establish a de facto governance regime on the Moon.

Robotics as a Service (chapter 8) will feature a deeply integrated environment with a wide array of touchpoints between stakeholders. As in the terrestrial environment, each interconnection relies on well-defined legal norms and protections, such as rights and limitations of the service provider to interface with another actor's assets and protections of intellectual property balanced with open information for operational safety.

Significant infrastructure development is necessary for the lunar economy particularly if it is human tended, as in ocean oil rig platforms. Landing pads (chapter 9); infrastructure hubs with habitats, farms, and waste management (chapter 10); and cislunar supply hubs (chapter 13) represent capital investments and maintenance commitments. An internationally respected and enforceable property rights regime will be vital for enabling such investment and concomitant provision of services and capabilities.

Railroads (chapter 12) are similar to wired power in that a linearly extensive but narrow easement may be required to place the rail line and maintain it, while an enforcement mechanism will help protect the line from damage from other activities. Like wired and wireless power, there will be hubs, junctions, and stations requiring property use protections.

Legal regimes implemented on the Moon will require international support to be effective and provide investor confidence. State and nonstate actors can be expected to test the boundaries of the legal regime, motivated by profit, power, or prestige. For example, lunar actors might assert assumed or conveyed rights through the lunar equivalent of "freedom of navigation" exercises, which will benefit from a predictable, broadly accepted, rules-based order to prevent conflict and resolve disputes. To that end, we turn now to an overview of the international legal framework.

16.2 International Space Law

The primary source of international space law is the 1967 Outer Space Treaty (OST). Ratified by every spacefaring nation, the OST contains two provisions especially pertinent to discussions of the lunar economy:

> *Article I*. 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 [hu]mankind . . .

> *Article II*. Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.[4]

Although treaties are addressed to states, the OST in Article VI makes state parties internationally responsible for the activities of their citizens. Commercial ventures require authorization and continuing supervision from their parent state. The language in Article II that prohibits national appropriation of outer space—which is sometimes called the "non-appropriation principle"—therefore has implications for LunA-10 activities, whether conducted by states or private entities. However, there is considerable disagreement about the meaning of "national appropriation." While it is clear that states may not claim any area of the Moon as sovereign territory, it is unclear to what extent a state may develop permanent fixtures on the surface of the Moon if the state maintains the right of exclusion for its fixtures.

Furthermore, exploitation of resources on the Moon remains a highly contentious topic among states and legal scholars. The United States, Luxembourg, Japan, and the United Arab Emirates maintain that commercial extraction of space resources by private citizens is permitted under Article II and have passed national laws in their countries codifying these property rights domestically. Russia, China, the Global South, and some of Europe hold the view that such extraction and exploitation must occur under the direction of an international body such as the United Nations. They cite Article I as further evidence that the OST requires a more coordinated approach for commercial space activities, potentially involving benefit sharing with non-spacefaring nations. The currently defunct 1979 Moon Treaty, which only has seventeen state parties, would have applied the legal principle of "common heritage of humankind" to the Moon. This principle, which most of the world (excepting the United States) agrees applies to the deep seabed, would have required actors to obtain authorization from a commons governance framework to exploit and extract space resources.[5]

By contrast, the Artemis Accords, a nonbinding set of bilateral diplomatic arrangements led by the United States, include in section 10 an affirmation that the signatories do not view the extraction of space resources as inherently a form of national appropriation under Article II of the OST. The Accords focus the use of such resources on "support for safe and sustainable operations" and "space activities," suggesting that in situ operational use may be considered more legitimate than extraction for commercial gain on the Earth.

Property rights are typically a function of national governments rather than of international law. The international space law regime does not codify such rights in detail, providing only a framework for spacefaring states to operate within. Because the framework itself is contested, the LunA-10 activities in part 2 of this *Field Guide* will require considerable legal development to secure a predictable rules-based order, likely including inputs beyond the OST in the form of customary international law. State practice, including states' reactions or failures to react to the activities of their private citizens, may play an important role in determining specific property norms for the lunar economy.[6] The next section analyzes potential allocations of property rights and their consistency with legal and economic considerations.

16.3 Property Rights Framework Analysis

Pershing summarizes five potential methods for allocating property rights in space.[7] Li similarly identifies five channels for accessing economic benefits of space resources under the global commons' governance regime.[8] These summaries provide helpful analytical models for discussion but are not specific to the Moon or the LunA-10 vision. Accordingly, in this section we synthesize and analyze property allocation models in the context of the lunar economy elements described in this *Field Guide*. We then evaluate the models to identify which are most likely to be effective in securing the necessary rule-based legal protections for sustainable investment in lunar development. Other important uses of the Moon such as scientific investigation and space tourism are not the focus of this analysis.

The first model involves property rights granted by the *right of first possession*.[9] In this model, once an entity establishes control of unowned land or resources on the Moon, that entity enjoys broad rights of use, control, exclusion, and transfer. This approach, generally favored by the United States for its adherence to the open market, would permit first-moving actors to secure property rights for all uses described in this *Field Guide*. However, subsequent actors may not be able to overcome market failures such as monopolies on valuable land or resources or free riding that causes underinvestment in shared infrastructure. Furthermore, this model relies upon a controversial interpretation of Articles I and II of the OST and is heavily disfavored by non-spacefaring nations. Scholars have noted that this regime invites a land rush and may extend the conflicts and concomitant costs representative of the colonial era to outer space. Such a regime may therefore have mixed success in fostering peaceful, predictable development of the Moon and its resources. However, this regime may be the most likely to apply in the absence of further legal and normative developments that regulate activities on the Moon.

The *right of continued use* is a modification of the first possession model where rights would be contingent upon continuous, active use of the resource or area.[10] This model contains many of the drawbacks of the first possession model, but, because a hiatus in occupation or operations permits an opening for competing claims, actors are discouraged from claiming vast areas or resources without the intention or capacity to use them effectively. This may be helpful in overcoming monopolies hindering the development of power systems, railroads, and infrastructure. Still, there could be inadequate diplomatic means to seize, or prevent seizure of, assets during a hiatus.

In contrast to decentralized approaches, *commons governance models* involve regulation by an international body such as the United Nations. For example, under models using reserved or allocated areas,[11] actors would be limited to developing or exploiting areas permitted to them by the international body. These models help address collective action problems like the "tragedy of the commons," wherein a resource that is common to all groups can be overtaken by one group.[12] This would allow actors to engage in the LunA-10 commercial activities within their designed areas but face potential inefficiencies in administration.[13] There are also issues with specific approaches to allocating areas. The *equal allocation approach,* where each nation gets the same acreage of lunar real estate, is considered inequitable by larger nations and makes no provision for unequal value of the allocated territory.[14] The *reservation approach*, which sets some resources aside for future development by currently non-spacefaring states, forces the international body to identify zones, reservation periods, and application conditions.[15] When resources are set aside, such reservation areas become less useful, hindering infrastructure development.

The *credit swap approach* contemplates an international agency that allocates to each country the rights to a portion of a set amount of space resources.[16] Spacefaring nations can access those resources directly, while spacefaring and non-spacefaring nations alike have the option to sell their credits on the open market. While the allocation of minerals, metals, and infrastructure appears straightforward, less thought has been given to allocation of power generation and delivery as well as PNT infrastructure and services. It is also unclear how the credits could be allocated in a manner widely perceived as equitable.

Finally, under a *leasing approach,* an international agency allocates property rights to nations on a leased basis, the defined rights persisting for the duration of the lease, which may be renewable.[17] The nations can then allocate their leasing rights to companies or individuals. Proceeds from the leasing fees may be shared with non-spacefaring nations on an equitable basis, the nature of which is undetermined at present. This approach has the distinct advantage of allowing state and nonstate actors alike to operate directly on the Moon, including with regard to real property, without violating Article II of the OST. However, finite leases may incentivize leaseholders to underinvest in long-term infrastructure or exhaust the local resources during exploitation.

16.4 Findings

This discussion is summarized in table 16.1. In the top portion of the table we evaluate, by approach, whether each of the proposed commercial services will have adequate protections for property rights. We compare these models against a scenario in which no property rights are conveyed or assumed, which would result in limited authority to conduct prolonged lunar commercial operations without further legal development. In the table, a checkmark reflects our belief that the property system would be an effective way to support the LunA-10 system or consideration reflected in the tests of approach. A question mark reflects our uncertainty or ambivalence about the suitability of the property system for the purpose of each LunA-10 system and listed considerations. An "x" reflects our belief that the property system faces serious problems in facilitating the LunA-10 system or struggles with respect to the listed consideration.

Table 16.1. Analysis of property rights regimes

Systems/Tests	*Property rights conveyed through:*					
	First possession	*Continued use*	*Reserved/ Allocated*	*Credit swap*	*Lease*	*None*
LunA-10 Systems						
Power systems	?	✓	✓	?	✓	x
Mining	✓	?	✓	✓	✓	x
Metal recycle	?	✓	✓	?	✓	x
Communications/PNT	✓	?	✓	?	✓	?
Robotics as a Service	✓	?	✓	?	✓	?
Infrastructure	?	✓	?	?	?	?
Railroads	?	✓	✓	?	✓	x
Tests of Approach						
Existing treaty compatibility	?	?	✓	?	✓	✓
Evolvable from existing CIL	✓	✓	✓	✓	✓	✓
Private actor rights	✓	✓	?	?	✓	x
State actor rights	x	x	✓	✓	✓	x
Relative international legitimacy	x	x	✓	✓	✓	✓

In our evaluation, approaches relying on the right of first possession and continued use effectively grant rights through occupation and defense of those activities by the authorizing state. These approaches also appear to be mutually complementary, with different economic strengths depending on the nature, duration, and continuity of the activity. However, we view these approaches as being questionable within the currently understood treaty environment. Rightly or wrongly, this may serve as a drag on diplomacy as the lunar economy seeks to find its footing. Over time, if these models were adopted, customary international law would likely evolve contemporaneously to legitimize the activities and fill in gaps in the treaty regime.

The commons governance models provide for equitable allocation of areas and resources, giving effect to Article I of the OST and soliciting buy-in from the non-spacefaring international community. Because the rights are granted through the mechanism of an international agency, these models are also consistent with the non-appropriation principle from Article II of the OST. Because rights for each lunar economy activity depend on authorization from the international body, we judge that there are risks from regulatory drag or lack of consensus, but that same mechanism provides a means for overcoming most other economic problems identified above. The strengths and weaknesses of the reservation and allocation approaches lie in part in the details of the proposals, which need further consideration. The credit swap approach offers a unique approach to mining, with unexplored potential on other topics. The leasing approach appears to have several unique strengths, with questions about the specifics of lease terms to secure long-term infrastructure development. Interestingly, this approach uniquely grants flexibility to the international body to allow nations to retain much of their preferred economic and legal models on the Moon.

In practice, this analysis demonstrates that the LunA-10 vision may be best served by considering a diversity of property allocation models tailored to different needs. For example, where resources are especially prone to monopolies (such as scarce water in shadowed craters or central land impeding potential paths for power lines and railroads), more regulated channels may be preferable to a first possession approach. By contrast, where the primary concern is a lack of investment incentives or a need for expeditious resource extraction and exploitation (or both), market-based models may be preferable. A diverse property regime may work as a compromise between spacefaring and non-spacefaring nations, facilitating the international cooperation necessary to kickstart the lunar economy.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Akin Gump Strauss Hauer & Feld LLP.
2. Raytheon.
3. Lattanze, *Architecting Software Intensive Systems; and The Open Group, TOGAF Version 9.*
4. UN, Outer Space Treaty.
5. Hamilton," Space and Existential Risk," 56.
6. Durkee, "Interstitial Space Law," 423.
7. Pershing, "Interpreting the Outer Space Treaty's Non-Appropriation Principle."
8. Li, "Analysis of the Channels for Accessing Economic Benefits."
9. Buxton, "Property in Outer Space"; and White," Real Property Rights in Outer Space."
10. Banerjee, "Extraterrestrial Habitation and Space Law"; and Fountain, "Creating Momentum in Space," 1753, 1777.
11. Li, "Analysis of the Channels for Accessing Economic Benefits."
12. Alexandra Spiliakos, "Tragedy of the Commons: Examples & Solutions: HBS Online," Business Insights Blog, February 6, 2019, https://online.hbs.edu/.
13. Hardin, "Tragedy of the Commons," 1243.
14. Cooper," Encouraging Space Exploration," 117; and Heim, "Exploring the Last Frontiers for Mineral Resources," 846.
15. Leib, "State Sovereignty in Space," 21.
16. Basu," Regulatory Mechanism for the Exploitation of Natural Resources"; Paxson, "Sharing the Benefits of Outer Space Exploration," 513–14; and Zell," Putting a Mine on the Moon," 492.
17. Williams, "Leasing the Moon"; Pershing," Interpreting the Outer Space Treaty's Non-Appropriation Principle"; and Sachdeva, "Commercial Uses of Outer Space."

17

Responsible Economics for Lunar Exploration, Use, and Market Growth

Bruce Cahan

Bruce Cahan is a Wall Street lawyer, HK merchant banker, geospatial technology finance pioneer, and lecturer at Stanford University's School of Engineering's Department of Management Science and Engineering and in the university's Institute of Design. He is CEO of Urban Logic Inc., a 501(c)(3) nonprofit, and CEO of Reimagineering Corporation, where he focuses on using design, finance and organizational theories, research methods, and prototyping to anticipate how large institutions must change to achieve functional innovation and meaningful inclusion of diverse innovators. Cahan is licensed as an attorney in California, New York, and Pennsylvania.

17.1 Introduction and Framing

The space economy is estimated to grow at 9 percent per year to reach $1.8 trillion by 2035, of which a portion will represent goods, services, and infrastructure assets for and from the lunar economy.[1] The Moon is essential for future space exploration and advancing the legal, market, and investment frameworks for off-planet economic and national security. The technical infrastructures for landing on the Moon and gathering its resources, some of which have been discussed in earlier sections of this *Field Guide*, are rapidly turning science fiction into everyday reality.

However, the market infrastructures for trading, hedging, financing, insuring, investing in, and storing the value of lunar resources of interest—and those who enable such private market infrastructures—remain under-researched and hypothetical. Ambiguities abound in specific dimensions that will define and evolve the lunar economic paradigm for years to come:

- Design principles. What would guide responsible innovators in establishing lunar economics?
- Activities that grow the lunar economy. What space or terrestrial activities, built in or for the lunar economy, are required for long-term growth?
- Legal framework. What laws exist or will evolve to protect the lunar economy?
- Ethical principles. In anticipation of, and in the absence of, a comprehensive legal system, what code of conduct should lunar innovators adopt?
- Dynamics of market adaptation. What parts of terrestrial market dynamics should be adopted, adapted, and used to accelerate lunar markets, and what guardrails for a sustainable, transparent marketplace should be included?
- Marketplace transparency and governance. Where would administration of marketplace rules be mediated, and how would violations be addressed?
- Readiness levels in context. When are innovations both technically feasible and ready for widespread economic deployment?
- Bankruptcy, reorganization, and the life cycle of companies. How should the lunar economy anticipate and redeploy the capital once claimed by failed companies or operations?

This chapter outlines a high-level framework of components through which the mutual self-interest of all parties operating on the Moon, or those seeking to invest in space activities enabling the lunar economy, can drive reductions in legal, operational, and financial risks. With a workable market infrastructure framework, conflicts over lunar resources can be reduced and the international benefits of lunar exploration can be achieved.

17.2 Design Principles for a Functioning Economy

Theoretically, economies follow historically validated principles but do not grow consistently.[2] Economic expansions and contractions (business cycles)[3] reflect stimuli (incentives, subsidies, and shocks), which in turn reflect and leverage market stakeholders' perceptions of *risk, return, asset type*s, and *maturity* (known as the four factors).[4] Once the Four Factors are computable and communicated transparently as market intelligence, investors can be agnostic in deploying their capital to derive the long-term stability of building portfolios. Such portfolios include diverse asset types that generate consistent returns by taking on modest risk over longer time periods.[5]

Six basic forms of capital generate value in an economy: human, natural, financial, manufactured, intellectual, and social/relationship (known as the six forms of capital or six capitals).[6] These forms of capital are resourced, recombined, and changed through nested processes. Financial capital flows are then based on the increase in value (or reductions in risk) provided to customers of the organizations operating these nested processes. A seventh form of capital exists in the rules by which economic activity—and stakeholders responsible for such activity—operate. This is known as legal framework capital.[7] Such rules for market function are either formalized and enforceable as a matter of law (for example, rules for assuring performance of contracts) or informal, in how participants in the marketplace define and transact goods, services, investment, extensions of credit (debt), and means for dispute resolution.[8]

In establishing responsible and responsive lunar economics, these design principles are a useful bedrock from which to start. The more formalized, enforceable, and responsive the rules by which an economy operates, the more likely it will attract investment and create productive capacity.[9] Brittle or overly complex systems of law or market function incapable of evolving along with the economic activity it regulates will undermine an economy's growth.[10] The six capitals, leveraging the ambiguities and certainties of legal framework capital, aim to create goods and services that functionally support or mitigate risk for activities that define an economy's outputs and growth, including lunar economy.

17.3 Incomplete Legal and Ethical Frameworks Facing the Lunar Economy

The generic term "space activities" appears in the 1967 Outer Space Treaty, but there is no standard list of what these activities might entail. Bespoke analyses show contributions to the US gross national product generated by commercial and government space customers, such as NASA.[11] Spacefaring nations are beginning to converge on sets of technologies for space activities that will define and grow the space economy. NASA's Technology Taxonomy hierarchically defined sets of space technologies as Tier 1 (17 sets), Tier 2 (72 sets), and Tier 3 (368 sets).[12] The European Space Agency's Technology Tree Taxonomy hierarchically defined twenty-five sets of Technology Domains and 104 Subdomains, branching down to 355 Technology Groups.[13] In general, technology taxonomies are bespoke processes for recruiting, financing, and organizing the six capitals necessary to develop and operate such technologies as economic system components.

As will be discussed in section 17.5, the space economy will grow when mechanisms are in place to improve market transparency of when supply and demand of each "space activity" converge. This may change with orbit region; a growth in one region (such as the Moon) may not have a direct link to growth in another region (such as Mars or geosynchronous orbit).

The commercialization of space has led national and global terrestrial economies to new interdependencies. In turn, the absence of a comprehensive legal framework for space activities and inadequacies in the legal systems for regulating the space economy have come into focus.[14] Today, participants in the space economy must navigate a patchwork of treaties, cooperative working partnerships, joint ventures, and individual country statutes. The United Nations (UN) Committee on the Peaceful Uses of Outer Space

(COPUOS) and the UN's Office of Outer Space Affairs (UNOOSA) have highlighted the need for filling gaps in the legal frameworks for space activities.[15] Some seek guidance from treatment of analogous terrestrial legal concerns, such as the UN's Convention on the Law of the Sea. However, the US and several other spacefaring nations have not adopted that treaty.[16] Exploration of space is echoing great power competitions on Earth, such as the US-led Artemis Accords for lunar exploration competing with China's sphere of alliances for the International Lunar Research Station.[17]

Without a comprehensive legal framework for the lunar economy, what principles—based on mutual self-interest and investment protection—can be found to guide development?

An unlikely source may be **the codes of conduct binding the professionals involved in building the lunar economy.** Engineers,[18] computer scientists,[19] data scientists,[20] designers,[21] logisticians,[22] medical professionals,[23] mathematicians,[24] statisticians,[25] and numerous other professions that contribute to space technology have developed their own codes of conduct. Just as their professionalism and talents converge in space activities that underlie a reliable lunar economy, their codes of conduct align on specific licensing, professional development, and ethical principles. This is how the expert group assures the wider community of responsible functional outputs and sustainable impacts.

Were these codes of conduct aggregated and aligned around core concerns—such as professional conduct (avoiding misconduct), respecting others' dignity and rights, transparent communication, and addressing risks and unintended consequences—an "aggregated code of conduct" would begin to emerge. This might serve to guide participants building and investing in the lunar economy.

Such an aggregated code of conduct would not directly fill the void of a comprehensive legal framework for the lunar economy. However, coupled with individual contractual remedies, this is at minimum a legally enforceable way to trace professional responsibility for errors and omissions affecting the lunar economy to their source.[26] It can also cause all stakeholders in a specific lunar investment to comprehensively assess their counterparty risk exposures and reciprocal quality assurance, both for initial hardware installation and ongoing operations.

17.4 Dynamics of Market Adaptation

Terrestrial economics date back to the earliest times of trading goods, specifically, transacting in specie (gold, silver) and the invention of financial instruments (such as credit facilities, futures, and options). Governments have used tools such as regulatory processes, currency control, tariff, taxing, procurement, subsidy, economic development credits, and lending powers to offset the pure free market capitalism of a given economy.

The lunar economy requires a fresh assessment of the policies used to stimulate the terrestrial economy and mitigate risk and inequity. For example: Insurance allows individuals, businesses, and even primary insurers to offload a portion of risks and liability exposures from their operations. Chapter 21 outlines unique insurance considerations facing the lunar economy today. Analysts are already sounding the alarm that infrastructure assets may be exposed to substantial risks due to climate change on Earth.[27] This may make lunar infrastructure an attractive diversification target for investors that have holdings today in terrestrial infrastructure, as long as such lunar operations were both profitable and insurable.[28]

As a reference point, financing lunar assets requires cognizance of how short- and long-term capital is deployed terrestrially. Consider a pension fund, foundation endowment, or institutional fund manager investing capital. Their portfolio is a pie split into slices, intended to grow return on investment (ROI) through specific financial strategies and tax-advantaged commitments and reduce exposures to market volatility over a certain time horizon.[29] The variety of asset classes available for portfolio managers is vast, allowing diversification of the sources of risk and returns.[30]

Investing as limited partners in venture capital funds means holding positions in target companies that need to become publicly traded (have an initial public offering) or get acquired within five years to generate a meaningful return. By its nature, commercial lunar infrastructure will be developed for longer term use and repurposing, more akin to industrial base and infrastructure assets on Earth. That will require companies seeking funds (equity or debt) to tell their "readiness level" stories and appeal to investors able to accept longer time horizons for an investment return.

17.5 Market Transparency and Governance

The lunar economy will attract a diverse array of innovators. One dilemma is whether, when, and how much of their innovations' successes and failures should be communicated to safeguard ongoing lunar operations and reassure financial stakeholders that past mistakes can be avoided. Generally, markets that have greater transparency create improved outcomes and reduce "uncertainty traps" that deter economic and investment activity and attract capital more consistently than markets with low or selective transparency.[31] However, greater transparency at the macro level of market efficiency contrasts with the legitimate proprietary technology and privacy concerns of space companies.[32] Transparency of lunar actors in the marketplace and their interactions with government regulations can have a profound effect on marketplace performance by reducing delays, administrative arbitrariness, corruption, and other factors.[33]

Commodity exchanges serve as terrestrial mechanisms for generating, aggregating, and transmitting market participants' predictions for trading in future demand and supply. One example of how this principle could apply to the lunar economy would be akin to the proposed **Space Commodities Exchange**, wherein commodities would be defined and the terms for trading them established in accordance with US Commodity Futures Trading Commission policies.[34] This includes five notional buckets of commodities for trading on the exchange: (1) raw materials, (2) financial indexes, (3) financial derivatives, (4) services, and (5) processed goods.

Commodities exchanges have unique features that fill gaps in the legal framework and can address other uncertainties surrounding the lunar economy. Commodities traded on an exchange contribute to the interoperability and cohesion of markets; a commodified product is reliably certain to be supplied and therefore incorporated into higher value services.

Members of the exchange can define what trades as commodities and how to enforce such trades. In doing so, the commodities contract itself becomes an asset, tradable or serving as collateral to grow the six capitals of the lunar economy. Finally, the rulebook that members of the exchange adopt can include provisions for resolving ambiguities in duties, rights, and remedies with other members, foreshadowing how commercial space laws and regulations can develop pragmatically and organically.

While NASA has been the US government agency leading technological development on the Moon, **to make meaningful progress toward a commercial lunar economy, a game-changing government organization entrant would likely be the US Treasury, which has yet to be involved in the lunar sphere**.

17.6 Readiness Levels in Context

In designing and building technologies for the harsh lunar environment, discussions often focus on Technology Readiness Levels (TRL)[35] and Manufacturing Readiness Levels (MRL),[36] both scaled 1 through 9. However, the lunar economy requires innovations that

- have a sustainable business case for servicing identified customers beyond the government paying the cost of goods and services offered (BRL: Business Readiness Levels);

- attract investors through the company's cycle of startup, pivots, growth, and repurposing (IRL: Investor Readiness Levels);
- build components or products that fit within a systems engineering model and within work processes of existing technologies (SRL: Systems Readiness Levels);[37] and
- can become interoperable as commodities to reduce obsolescence and scale adoption (CRL: Commoditization Readiness Levels).[38]

As space companies go from start-ups to mature companies selling services, a more comprehensive set of readiness levels allows for a greater diversity of financial engineering solutions. With such a paradigm in place, entrepreneurs, investors, customers, and regulators will have a more predictable ecosystem. Some features of this ecosystem include innovations that become usable and functional components of the lunar economy; knowledge of how to deploy the six forms of capital in a balanced portfolio to assure adequate resourcing and operational capabilities for a nested economy; and clusters and supply chains of industrial base components to monitor for readiness level benchmarks that determine financial liquidity.

Readiness levels and the Space Commodities Exchange can spur innovations in insurance-linked derivatives, infrastructure bonds, and other forms of financially engineered assets that further grow the lunar economy's capacity to fund itself. Quantifying a broader set of readiness levels also allows new forms of storytelling, whereby space companies quantifiably communicate their maturity to lenders and investors and attract financial capital beyond early-stage speculative grants and venture funds.

17.7 The Life Cycle of Companies: Bankruptcy in the Lunar Economy

Like the growth and renewal of forest and marine ecosystems, entrepreneurship is an organic process. The life cycle of companies is a continual process of growth or decay.[39] Companies with limited or faulty readiness level achievements may be ultimately forced to sell off their assets or reorganize through bankruptcy or similar processes.[40] Notable bankruptcies of space companies are causing national credit rating agencies like S&P Global Ratings and investors funding space companies to adjust their appetite and premiums.[41] Furthermore, wherever fragile business activities exist, fraudsters may follow, as noted in association with Virgin Orbit.[42]

The US bankruptcy process allows managers, investors, and customers sufficient time to propose new business models (BRL predicates) that can make practical use of the company's human capital and intellectual property. If the lunar economy is in a formative state, such as the Foundational Age described in chapter 14, and an infrastructure company fails, the US government could consider intervening in the bankruptcy process to acquire and secure the company's six capitals for the overriding public interest on an interim basis. Similarly, it is worth considering the impacts of foreign acquisition or control of a fragile lunar company, particularly if the foreign country is not aligned with the principles of the Artemis Accords or the Outer Space Treaty.

17.8 Recommendations by Lunar Age

This chapter briefly reviewed key trends, principles, and recommendations for financial engineering the lunar economy as a component part of the expanding space economy. As mentioned in chapter 14, the lunar economy's future likely will develop in four phases, the first three of which are discussed here:

- Exploration Age of discovering the potential of using the Moon as a "new continent" that opens economic and scientific opportunities,

- Foundational Age of early-stage investments in minimum viable experiments for commercial capabilities to be sourced on or for the Moon, and
- Industrial Age of scaling up and commoditizing such commercial capabilities.

Recommendations suitable to each period should optimize and leverage the six capitals to fully accelerate the lunar economy.

17.8.1 Exploration Age

For the Exploration Age, the author makes the following eight recommendations:

1. Define the nature and quantity of "space activities" that will be required for the early Industrial Age to become sustainable.
2. Determine the interdependencies of such space activities based on a "periodic table of quality" of lunar operations lifecycles, analogous to the periodic table of chemical elements.
3. Define the Readiness Levels and benchmarks that will track such space activities' progress individually and as interdependent clusters.
4. Scope the nature, diversity, and quantity of six capital resources that would be required to be committed to such space activities, assuming the Industrial Age were to begin in 2034–35.
5. Recruit commercial, financial, and government members for a Lunar Board of Trade to establish the Space Commodities Exchange and agree on the rules for defining and trading lunar commodities.
6. Clarify the legal framework through which the six capitals will percolate and be consistently enforceable.
7. Adopt a lunar economy code of conduct to serve as an evolving ethical framework for space activities on or relating to the Moon.
8. Establish university curricula, professorships, research laboratories, and executive education programs to improve the human, networked, and intellectual capital available to grow the lunar economy.

17.8.2 Foundational Age

For the Foundational Age, the author makes the following six recommendations:

1. Create annual statistical data reports that track the space activities being developed and funded for the lunar economy and analyses of where these activities need additional resources from the six capitals to meet timeline targets for the Industrial Age.
2. Establish a Center for Space Finance, Insurance, and Market Formation to
    a. Create, analyze, and publish consistent econometrics for the development and financing of the lunar economy and continuously research its market mechanisms;
    b. Track and publish case law, decisions, and legal analysis involving the lunar economy's legal framework; and
    c. Track and publish reports on the competitive landscape of the lunar economy, including issues of concern for national security.

3. With US Commodities Futures Trading Commission approvals, begin operating the Space Commodities Exchange by offering commodity contracts for services, derivatives, and indices relating to the lunar and cislunar economy.

4. Begin defining the raw materials and processed goods available to be traded on the Space Commodities Exchange.

5. Survey and annually re-survey US government agencies for the grants, investments, and acquisition commitments they are making for space activities on the Moon and which of such activities can become commercially available rather than bespoke. By necessity, this means a broader investment pool than just that of NASA.

6. Seek credit rating agency due diligence checklist and approval for issuance of credit ratings of project finance and infrastructure financial instruments whose proceeds fund the lunar economy.
    a. Establish a Lunar Development Industrial Bank with authority to raise capital, invest in and restructure companies and projects benefiting the lunar economy.
    b. Analyze the competitive landscape available to US companies, investors, and customers in pursuing, investing in, and using space activities in the lunar economy, versus those available in and from other spacefaring nations.
    c. Survey and annually re-survey the human capital committed to the lunar economy and assure that it represents a healthy diversity of talent by race, gender, age, and other demographic characteristics.

17.8.3 Industrial Age

For the Industrial Age, the author makes the following four recommendations:

1. Add the raw materials and processed goods buckets to the services, derivatives, and indices available to be traded on the Space Commodities Exchange.

2. Require US government agencies to buy commodities offered on the Space Commodities Exchange to avoid the high cost and uncertain availability of developing bespoke acquisition arrangements.

3. Update the legal framework for the lunar economy, including adjudication of disputes, to keep pace with claims involving relevant or desired space activities or commitments of the six capitals.

4. Analyze sources of fragility, illiquidity, business risk, and business failure within the burgeoning lunar economy, and solutions for mitigating such risks.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

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2. Morck and Yeung, "Economics, History and Causation."
3. National Bureau of Economic Research, "U.S. Business Cycle Dating."
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5. Koumou, "Diversification and Portfolio Theory."
6. Integrated Reporting Framework.
7. See discussion of legal framework later in this chapter.

8. Pistor, "Legal Systems and Economic Development."
9. Aldashev, "Legal Institutions, Political Economy, and Development."
10. Ruhl et al., "Resilience of Legal Systems"; Howard, *How Law Is Suffocating America*; and Gibney, *The Nonsense Factory.*
11. Highfill and MacDonald, "Estimating the United States Space Economy."
12. NASA, "2020 NASA Technology Taxonomy."
13. European Space Agency, "ESA Technology Tree Version 4.1."
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15. United Nations Office for Outer Space Affairs, "Space Law Compendium"; and United Nations Office for Outer Space Affairs, "Space Law Treaties and Principles."
16. UN General Assembly, "Convention on the Law of the Sea"; US Department of State, "Law of the Sea Convention: Timeline"; and Kraus, "Unmoored from the UN."
17. Pollpeter et al., "China-Russia Space Cooperation"; MacDonald et al., *China and Strategic Instability in Space*; Delgado López, "Why the Space Dimension of the Expanded Alliance Matters"; and Bilal, "Advent of Astropolitical Alliances."
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19. "ACM Code of Ethics and Professional Conduct," Association for Computing Machinery, June 22, 2018, https://www.acm.org/; and Michael Loui and Keith Miller, "Ethics and Professional Responsibility in Computing," Online Ethics Center, August 23, 2007, https://onlineethics.org/.
20. "Data Science Code of Professional Conduct," Data Science Association, http://www.datascienceassn.org/.
21. *Professional Standards, Society for Experiential Graphic Design,* November 2014, https://media.segd.org/; and "Professional Code of Conduct for Designers," International Council of Design, proposed September 2020, https://www.theicod.org/.
22. "Code of Ethics," International Society of Logistics, http://www.sole.org/.
23. "Principles of Medical Ethics," American Medical Association, revised 2001, https://code-medical-ethics.ama-assn.org/.
24. "Ethical Guidelines of the American Mathematical Society," American Mathematical Society, revised January 2022, http://www.ams.org/.
25. "Ethical Guidelines for Statistical Practice," American Statistical Association, February 1, 2022, https://www.amstat.org/.
26. In general, professional malpractice and other theories of tort or contract liability can be claimed where (1) a duty of reasonable care or a duty to apply special skill is shown to exist, (2) the facts show such duty was disregarded or breached, and (3) provable damages occurred that would not otherwise have been suffered. The aggregated code of conduct and its parent codes of conduct would establish the duty (#1) and if disregarded, the breach of that duty (#2).
27. Adam Smith, "2023: A Historic Year of U.S. Billion-Dollar Weather and Climate Disasters," January 8, 2024, https://www.climate.gov/; and Munich RE, "Record Thunderstorm Losses and Deadly Earthquakes: The Natural Disasters of 2023," January 9, 2024, https://www.munichre.com/; and Munich RE, "Natural Disaster Risks: Rising Trend in Losses," https://www.munichre.com/.
28. International Project Finance Association (IPFA), *Infrastructure Monitor 2023: Global Trends in Private Investment in Infrastructure*, IPFA, 2023, https://www.ipfa.org/. See chapter 21 for more on the role and difficulties of insurance in the lunar economy.
29. The CFA Institute offers a series of books on Portfolio Management, such as: *Portfolio Management in Practice*, vol. 1, *Investment Management* (Wiley, November 2020), https://www.wiley.com/.
30. According to the Callan Institute, "The Callan Periodic Table of Investment Returns conveys the strong case for diversification across asset classes (stocks vs. bonds), capitalizations (large vs. small), and equity markets (US vs. global ex-US). The Table highlights the uncertainty inherent in all capital markets. Rankings change every year. Also noteworthy is the difference between absolute and relative performance, as returns for the top-performing asset class span a wide range over the past 20 years." Jay Kloepfer, *The Callan Periodic Table of Investment Returns: Year-End 2023* (Callan Institute, 2024), https://www.callan.com/.
31. Brown and Martinsson, "Does Transparency Stifle or Facilitate Innovation?"; Merlo et al., "Benefits and Implementation of Performance Transparency"; Pronovost et al., "Fostering Transparency"; Fajgelbaum et al., "Uncertainty Traps"; and Moshi, "Capital Flight and Institutional Frameworks."
32. Bernstein, "Transparency Trap."
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34. The design for the Space Commodities Exchange reflects research, briefings, working papers, and proposals, including: Cahan et al., "Outer Frontiers of Banking"; Cahan et al., "Space Commodities Futures Trading Exchange"; Cahan and Locke, "Space Commodities in Service of National Security"; and Cahan and Sadat, *US Space Policies for the New Space Age.*
35. US Department of Defense, *Technology Readiness Assessment Guidebook*, 5–9.
36. US Department of Defense, *Manufacturing Readiness Level (MRL) Deskbook*, 15.
37. Ross, "Application of System and Integration Readiness Levels."
38. Sean Ross, Bruce Cahan, and Ethan Strijbosch, "Lean Technology Development Baseline using Readiness Level Metrics" (pending publication); Sean Ross, Bruce Cahan, and Ethan Strijbosch, "Metrics for Lean Technology Development" (pending publication); and Optics & Photonics News, "Avoiding the Valleys of Death."
39. Michelin et al., "Evaluation of Entrepreneurial Behavior of Technology-Based Companies"; and Adizes Institute, "Organizational Lifecycle, https://www.adizes.com/.

40. For a sampling of fragile aviation and space companies, search for "aerospace" or "orbit" on Reuters, Distressed Asset Central, https://www.dailydac.com/. The discussion of where such asset sales should occur and what bankruptcy court would have jurisdiction is unclear considering the ambiguity of legal framework for claiming lunar assets, described in section 15.4.

41. More details in chapter 21. Also see Barry et al., "3 Satellite Bankruptcies in 3 Months."

42. Securities and Exchange Commission v. Matthew Brown et al. (US District Court for the Northern District of Texas), Civ. Action No. 4:24-cv-00558, https://www.sec.gov/; and Stempel, "US SEC Sues."

18

Rules-Based Frameworks via a Lunar Development Cooperative

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18.1 Today: The Absence of Rules-Based Frameworks on the Moon

The continuing industrialization of the Moon, as envisioned by LunA-10, hinges on creating enforceable rules to govern economic activity. Without enforceable rules, commercial activities can fall prey to "tragedy of the commons" scenarios, where parties exploit resources inefficiently and unsustainably. Monopolies can emerge, hindering competition, harming consumers, and potentially sparking conflicts that result in lost assets, trade barriers, and heightened risks.

In the short term, the international community is unlikely to develop an adequate rules-based framework on its own, for several reasons:

- Agreement on standards. The development of interoperability standards is critical, as discussed in chapter 22, but governments are unlikely to reach sufficient consensus to make these standards binding and enforceable standards within a reasonable period. Despite such community-driven efforts, it is unlikely that governments will achieve consensus on the standards, rights, and obligations needed to govern space activities within a reasonable period. While agreements like the Artemis Accords are an important step, they are too general to effectively govern commercial activities. They reflect the reality that it is far easier to reach an agreement on general principles than on detailed, implementable, and enforceable rules.
- Rules that support economic activity. Even if governments do agree on specific rules, given the many proposals that would limit the commercial exploitation of space,[1] it is uncertain that the rules will support, rather than hinder, the space economy.
- Implementation and enforcement. Even if governments agreed on a set of rules conducive to economic activity in space, nation-states likely lack the political will or resources to prevent violations.[2] Their attention will likely be directed more toward gaining military advantages or their own commercial endeavors rather than maintaining necessary market institutions, such as those discussed in chapter 17.

18.2 Tomorrow: Evolving and Enforceable Rules for the Space Economy

A Lunar Development Cooperative (LDC) is proposed to help address this dilemma by serving as the framework for deploying and managing future lunar infrastructure. The LDC would be a commercial endeavor financed and directed by commercial space users and investors to provide critical infrastructure. It would acquire and deploy infrastructure solutions such as those discussed in this *Field Guide*: power stations; communications/positioning, navigation, and timing nodes; a lunar rail; remote sensing; resource recycling; insurance; a cislunar logistics "harbor"; fuel and material storage depots; and more.

The LDC would be controlled by the space economy participants and other parties who voluntarily invest in it. The initial capital could come from the mechanisms discusses in chapter 17 or from entrepreneurs who have pooled their money to develop the infrastructure they need. These entrepreneurs would therefore have a vested interest in keeping the Moon open and conflict-free or other mechanisms discussed in Chapter 17. As the barriers of entry to space rapidly decrease, entrepreneurs will be incentivized to invest in shared infrastructure and rules. States could provide additional support, such as through sovereign wealth fund investments, loan guarantees, and nonfinancial assistance, which reduces the risk profile for larger, more risk-averse investors.

These investors would shape the rules that users of LDC infrastructure must abide by. Such rules would have a public aim and cover harmful interference between users, resource wastage, interoperability, and other issues necessary for economic, social, and environmental sustainability in space. These rules would be incorporated into contracts with infrastructure users, making infrastructure use conditional upon compliance.

The LDC could enforce these rules by imposing fines on violators, with fines varying based on the nature of the violation. Nongovernmental bodies have used fines to effectively regulate various common-pool resources, including water, fisheries, and timber forests.[3] The LDC's contracts could give it the right to sue users who violate its rules or fail to pay fines.[4] These suits could be brought to arbitration or to a court of a nation where the user holds assets.[5] Ultimately, the LDC could limit or terminate noncompliant users' access to certain services.

Once the LDC's infrastructure is operational, users' behavior will provide valuable information about which of the LDC's rules work and which do not. As an entity governed largely by space users and driven by the commercial imperative to attract and retain customers, the LDC will be incentivized to update its rules based on this feedback. Consequently, the LDC's rules are likely to be more responsive to space economy participants' needs than those of a government or intergovernmental body.

18.3 A Path to Lunar Property Rights

The LDC would not be a state, and per the Outer Space Treaty, it could not assert sovereignty or claim ownership of land in space.[6] However, *it could recognize and allocate rights that loosely function as limited property rights for its infrastructure users*. For instance, the LDC could invite its users to notify it of their intention to use or develop areas of the lunar surface or utilize specified resources for a set duration. The LDC could then evaluate and record these notices in a public registry and develop rules controlling other infrastructure users' ability to interfere with these registered activities. A user's fee for membership in the LDC would be priced on the estimated market value of the rights they have recorded.

As these rights become more established, they could be transacted with other LDC members. This system could eventually form the basis for a formal property rights regime if eventually transferred from the LDC's registry to an official one.

There are limitations to this model. Unlike a state, the LDC could not directly enforce its rules against parties not under contract with it, nor could it prevent competition from other infrastructure providers. However, these limitations could become assets. Competition could drive the LDC to create superior rules and infrastructure. If it can create pockets of good governance and economic growth in the areas benefiting from its infrastructure, more parties will want to locate themselves in these areas. By comparison, ungoverned or badly governed areas will tend to attract few parties, with a larger proportion being bad actors.

18.4 Conclusions

Though it would not be a state, the LDC could perform many of states' essential functions, including rights protection and public goods provision. Throughout history, nongovernmental, cooperative organizations have filled similar gaps, especially in frontier settings outside the effective reach of governments.

Space is such a setting. Current political and legal realities make it impractical for governments to drive a rules-based framework for the space economy, but this does not mean that space needs to be ungoverned. Concepts like the LDC enable space to be governed by the organized resources of space users to further the LunA-10 vision and the lunar economy.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. For instance, current proposals to create a centralized international authority that tightly controls access to space modeled after the Antarctica Treaty or the International Seabed Authority would likely impede development. For examples of these current proposals, see Brandon Dekema, "To Infinity and Beyond: Shifting the Space Regulatory Framework to Create Conservation-Minded Expansion," *Natural Resources Journal* 62, no. 2 (2022), https://digitalrepository.unm.edu/; and Jonathan Sydney Koch, "Institutional Framework for the Province of All Mankind: Lessons from the International Seabed Authority for the Governance of Commercial Space Mining," Astropolitics 16, no. 1 (2018), https://doi.org/10.1080/14777622.2017.1381824. Widely accepted economic theory and numerous empirical findings indicate that such regulators will tend to lack the knowledge, incentive, and flexibility to develop and adjust rules suited to a local context. See, for example, Elinor Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action* (Cambridge University Press, 1990).
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3. Ostrom, *Governing the Commons*.
4. Importantly, the LDC's founding instruments and user contracts would obligate it to abide by standards, implement safeguards, and grant enforceable legal protections to infrastructure users, ensuring its power is kept in check.
5. Under the New York Convention, awards issued by an arbitrator can be enforced and collected against assets held by a party in almost every nation on Earth.
6. Specifically, UN, Outer Space Treaty, Articles I and VI.

19

Case Study: Air Traffic Control in Antarctica

Elizabeth Hyde and Jeffrey Gehringer

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19.1 Introduction

The Moon has tantalized humanity for millennia—being in sight, but out of reach. The South Pole similarly tantalized explorers during the Heroic Age of Antarctic Exploration. This era of the late nineteenth and early twentieth century brought legends in the form of Roald Amundsen and Sir Robert Scott, the first humans to reach the South Pole in 1911/1912 (the Neil Armstrong and Buzz Aldrin of their time) and the survival of Sir Ernest Shackleton and the ill-fated *Endurance* (paralleling Jim Lovell and *Apollo 13* in 1970). While the early journeys to both Antarctica and the Moon were efforts to plant a flag, subsequent voyages have focused on scientific investigations. Although the Heroic Age predates the Space Age by fifty years, many of the physical, technological, and logistical trials of these expeditions are shared by both regions.

Both the Antarctic Treaty[1] and the Outer Space Treaty[2] embody fundamental principles of international cooperation and peaceful exploration. The Outer Space Treaty explicitly prohibits the placement of weapons of mass destruction on celestial bodies like the Moon, fostering an environment conducive to collaborative missions free from military competition. Similarly, the Antarctic Treaty prohibits the carrying out of strictly military maneuvers and the testing of any weapons. The Antarctic Treaty has transformed a vast icy terrestrial continent into arguably the world's most collaborative and peaceful region, where the national Antarctic programs work to advance scientific understanding and protect Earth's delicate ecosystems.

The United States Antarctic Program (USAP), managed by the US National Science Foundation (NSF), exemplifies this cooperative spirit. The USAP maintains a robust scientific presence and promotes international collaboration. Fifty-seven countries are party to the Antarctic Treaty, and many operate year-round in Antarctica today, underscoring the treaty's enduring relevance and global cooperation in scientific exploration.[3]

With these similarities in mind, this chapter uses USAP operations as a case study to investigate how lessons learned from Antarctica may apply to logistical, operational, and legal challenges on the Moon. Air traffic control (ATC) in Antarctica provides an interesting case study, as it requires communication and coordination with a variety of actors: participating pilots and ground crew, neighboring jurisdictions, and private enterprise. Lessons learned from ATC operations in Antarctica may guide future lunar framework designers in how to ensure a cooperative, international, and interoperable future on the Moon and not get stuck in bureaucratic ice.

19.2 Deconflicting Vehicle Movement in a Land with No Borders

Question: With the proliferation of rovers for prospecting, mining, and construction and multiple countries involved in those operations, under what authority can the movement of vehicles be controlled in a land with no borders?

The International Civil Aviation Organization (ICAO) is a United Nations (UN) agency tasked with establishing and recommending standard procedures and the "rules of the sky." Each UN member state uses these recommendations to create its own regulations. ICAO has established flight information regions (FIR) that denote which country acts as air traffic control over what airspace. In general, each country controls the airspace over its land. Over the open ocean and Antarctica, the coastal countries deconflict and are responsible for the airspace over international waters. Five countries control FIRs that cover the Antarctic continent: New Zealand, Chile, Argentina, South Africa, and Australia.[4]

The National Science Foundation's (NSF) McMurdo Station is the largest station in Antarctica and is managed by USAP. Home to over 1,000 personnel in the austral summer and three airstrips, McMurdo is the logistical center for the USAP and the greater Ross Island area. Scott Base (New Zealand) is a short distance away, and Italy, South Korea, Germany, and China all have stations in nearby Terra Nova Bay.[5] Ross Island is located inside the Auckland (New Zealand) FIR. To enable the large volume of air traffic going into McMurdo Station, the USAP has signed letters of agreement (LOA) with the New Zealand air traffic authorities.[6] The LOA establishes the McMurdo Sector Area (MSA), where the USAP controls aircraft movement during the summer season. A control center is on-site at McMurdo Station, with a remote operating facility in Charleston, South Carolina.

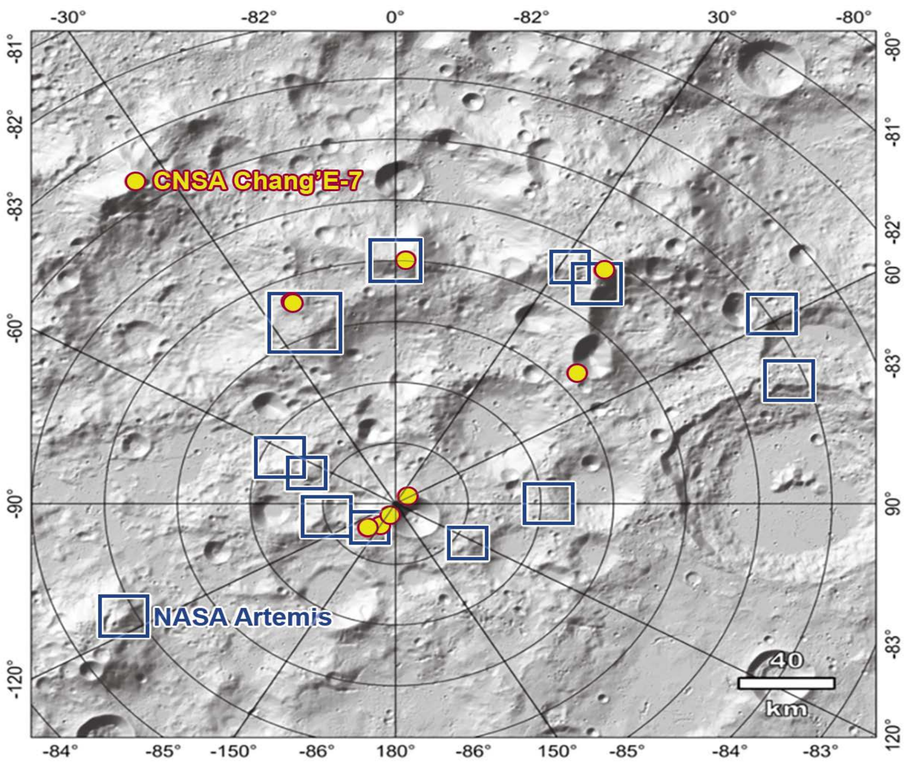

Figure 19.1. Planned US (NASA, Artemis) and China (CNSA) landing sites in the south pole region

Extending this analogy to surface traffic management on the Moon, control zones may be established in various areas of high activity. Figure 19.1 shows the planned NASA Artemis and Chinese landing sites, with clear proximity in and around the south pole, specifically the Shackleton crater. As these missions begin to land and operate around each other, an international organization similar to ICAO may be useful to set up agreements with neighboring users to facilitate overlapping and deconflicted control areas, like the Antarctic MSA. Operations may differ across regions and missions, such as lunar rail tracks or large-scale regolith movement areas around ISRU plants. Nevertheless, standard operating procedures will be key to safe, deconflicted operations, regardless of the operational control entity (if controlled at all).

19.3 Off-Nominal Conditions and Vehicle Emergencies

Question: In areas of high traffic, how do you ensure operations are separated, and what happens if a vehicle experiences an emergency?

Standard operating procedures become critical when routine operations become nonstandard. In typical instrument flight rules operation, alternate airports are required in case poor weather at the intended airport inhibits landing. In Antarctica, due to the long distances and minimal infrastructure, this is modified to a point of safe return, where an aircraft can turn back to New Zealand if the weather prevents landing at McMurdo Station. Even with this procedure in place, conditions change dynamically. USAP has established a whiteout landing area (WLA) as a safety measure. If a flight destined for a McMurdo runway or skiway cannot successfully execute an instrument approach due to adverse weather, the alternative is a landing in the WLA. The area is surveyed annually and certified as free of crevasses or obstructions. Each season, a WLA approach procedure is developed, which includes missed approach guidance from nearby airfields.

A clear lunar analog of the WLA is the concept of "safety zones" as established in the Artemis Accords.[7] The coordination of activities in those safety zones is important, particularly as the scale of the lunar economy grows and new inexperienced commercial players join the ecosystem. If an event such as a heavy-lift landing is to occur, other participants in the area must be made aware so they can clear the area or prepare to act if an off-nominal event were to occur.

In Antarctica, the air traffic control apparatus takes on this duty. On the Moon, building resilient infrastructure, emergency procedures, and open communications protocols between all nations operating in a given area will ensure continued safe operation.

19.4 Tourism and Deconfliction of Nonaffiliated Vehicles

Question: What happens when an unaffiliated private entity enters the control zone, such as a tourism provider? How do non-USAP affiliated aircraft interact with ATC?

Tourism in Antarctica has grown in popularity, attracting visitors eager to witness Antarctica's stunning landscapes and iconic wildlife, such as penguins and seals. Due to the increasing number of visitors (over 100,000 visitors in the 2022–2023 season[8]), the Antarctic Treaty is developing a framework for regulating tourism in Antarctica. Access to Antarctica is primarily through cruise ships, yachts, and air transport. All tour companies and visitors in Antarctica are required to adhere to regulations under the Antarctic Treaty, emphasizing environmental stewardship through the Protocol on Environmental Protection.[9]

The International Association of Antarctica Tour Operators (IAATO), established in 1991, plays a crucial role in managing this industry, advocating for safe and environmentally responsible tourism practices. During the austral summer, helicopter excursions from tour ships coordinate with McMurdo ATC. While ATC does not restrict airspace access in Antarctica, operators are encouraged to coordinate closely to ensure safe operations, especially in congested areas. ATC provides USAP flight following procedures, maintains situational awareness of local flights, and offers services to all operators upon request.

Tourism represents a parallel to emerging private industry on the Moon and its interactions with governmental groups. When governments sign treaties, private enterprises in those countries are now held to the same standard. The IAATO is an example of how private industry can band together, outside of mandatory regulation, to accomplish commercial goals while adhering to the environmental standards of the Protocol on Environmental Protection. Private companies on the Moon should aim to follow a similar model to IAATO and use standardized means of communication to keep all lunar operators informed while promoting mutual safety, even if not required by law or regulation.

19.5 Changing Established Procedures at the Pace of Emerging Technologies

Question: Once regulations and procedures are established, they are administratively hard to change. How do procedures change at the pace of emerging technology?

Uncrewed aerial systems (UAS) have revolutionized science data collection on Earth. Remote sensing data once requiring expensive airborne campaigns, tedious field campaigns, or satellite subscriptions can now be achieved with a couple of researchers and a drone. However, this democratization of the skies has presented an additional challenge: how to integrate UAS into the National Airspace System.

UAS operations in Antarctica have grown exponentially. In 2023, USAP and Antarctica New Zealand conducted over 150 UAS flight hours across fourteen different groups. USAP has developed a strict regulatory framework, with ATC responsible for the challenge of safely integrating UAS with manned aircraft. UAS operators are required to submit a concept of operations (CONOPS) to the NSF, which must be reviewed and approved. Pilots must be FAA Part 107 certified, provide flight and maintenance logs, coordinate their flight schedule with ATC, and send USAP flight planners their intent to fly twenty-four hours prior to flying. Once this intent to fly message is received, ATC issues a Notice to Air Missions (NOTAM), which is published widely. The ultimate goal is for each manned aircraft and UAS operator to have full situational awareness before takeoff and during flight. Other national Antarctic programs are members of the Council of Managers of National Antarctic Programs (COMNAP). Through COMNAP's aviation expert meetings, the USAP model (and CONOPS example) serves as a best practice for similar UAS policy between other member nations. COMNAP members have slightly different approaches, but all typically share UAS plans for situational awareness. Communication between these groups helps maintain general flight safety awareness.

For the Moon, uncrewed aerial systems represent an example of a disruptive technology that traditional regulations did not predict. On the Moon, uncrewed systems will be tightly integrated with crewed operations. The main takeaway from UAS integration is that while today's regulations and procedures may not account for future developments, they need to be flexible enough to adapt to new technologies. For instance, right-of-way regulations should be written in such a way that a new vehicle type (such as lunar rail) can be integrated into legacy systems (roads) without significant reinvestment or forced obsolescence. Providing greater situational awareness of every nation's plan for all lunar users will increase the ability of legacy systems to adapt to new technologies and interoperate even across nation-specific hardware.

19.6 Conclusions and Lessons Learned

Society is on the verge of creating new communities and economies on the Moon. Beyond the technical challenges, logistical questions remain. How will transit activities on the Moon be organized and managed? What international organizations will oversee the safe and efficient transport of equipment, in orbit and on the surface, in accordance with international law? How will the international community integrate and establish safety zones, monitoring schemes, and communications protocols? Air traffic control operations in Antarctica provide an analog for these questions from an implementation and legal point of view, embedded within an internationally agreeable concept of operations.

This chapter outlines how standardized operations, contingency plans, and adaptations are achieved in the Antarctic environment, but the common threads are collaboration and communication. Creating standards under governing bodies such as ICAO or industry trade groups such as IAATO allows all entities to be on the same operational page. Emergencies and off-nominal conditions must be considered, since they may have an outsized impact on surrounding operations. Operational plans must also be adaptable, especially when disruptive technologies enter the ecosystem. Communication and collaboration are the keys to a peaceful, sustainable, and international future, both in Antarctica today and on the Moon tomorrow.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. The Atlantic Treaty, December 1, 1959, https://www.ats.aq/.
2. UN, Outer Space Treaty.
3. Atlantic Treaty.
4. For detailed information about airspace and how it is controlled, see "Airspace," chapter 15 in *Pilot's Handbook of Aeronautical Knowledge*, 2023 ed., *Federal Aviation Administration*, https://www.faa.gov/.
5. For detailed information on these facilities, refer to US Antarctic Program Interagency Air Operations Manual, National Science Foundation, 2023, https://www.usap.gov/.
6. Civil Aviation Authority of New Zealand (CAA) and Airways Corporation of New Zealand (AWC).
7. Excerpt from section 11, Deconfliction of Space Activities: "The Signatories intend to provide notification of their activities and commit to coordinating with any relevant actor to avoid harmful interference. The area wherein this notification and coordination will be implemented to avoid harmful interference is referred to as a 'safety zone.' A safety zone should be the area in which nominal operations of a relevant activity, or an anomalous event could reasonably cause harmful interference." NASA, "Artemis Accords."
8. International Union for Conservation of Nature, "Impacts of Tourism in Antarctica," June 2023, https://www.iucn.org/.
9. Secretariat of the Antarctic Treaty, "The Protocolon Environmental Protection to the Antarctic Treaty," n.d., https://www.ats.aq/.

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Biomanufacturing in Space and on the Lunar Surface

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20.1 Introduction and Framing

While technological support of a thriving industrial economy has been extensively discussed, this *Field Guide* will now touch upon technologies that directly support a *human* presence on the Moon. The ability to sustainably produce molecules and materials via biomanufacturing, with reduced reliance on traditional chemical synthesis precursors, can provide integrated solutions for remote or austere locations both on and off Earth.[1] This is especially true on the lunar surface; by utilizing water as a solvent, biomanufacturing can be integrated with water capture and recycling processes required to support human activity. Mission-critical inventories of de novo synthesized components of food, pharmaceuticals, and materials will be critical to a future where humans are part of a thriving lunar ecosystem.[2]

In addition to mechanical, physical, and chemical approaches, microorganisms will help enable long-term activities. These activities may rely on in situ resource utilization (ISRU), manufacturing, energy collection, and energy storage, but the efficiency of biotechnology becomes particularly disruptive when biological efforts are used with locally available resources and optimized toward closed-loop systems. Loop closure, which indicates the recycling and reuse of resources toward the establishment of a circular economy, is key to minimizing the costs of resupply from Earth and also to ethical considerations associated with space waste generation and the preservation of environments.[3]

Tailored in-space biomanufacturing has emerged as a promising approach by which to create bio-enabled structures from source material such as lunar regolith or waste streams, produce industrial materials such as fuels and lubricants (given some Earth-sourced starting materials), or even biomine rare earth elements present in trace concentrations.

This chapter outlines technological achievements toward engineering microbes for space conditions and forecasts how biotechnology and biomanufacturing could contribute to an economically sustainable space and lunar economy.

20.2 Alternative Feedstocks for Closed-loop Systems

Biological systems often offer advantages in terms of power consumption, with many biologically inspired processes operating at standard temperatures and pressures. To fully realize ISRU and the potential for closed-loop systems that incorporate biology, microbes engineered to use novel feedstocks for growth and production should be leveraged. The recent Decadal Survey from the National Academies of Sciences, Engineering, and Medicine highlighted the critical importance of bioregenerative life support systems, loop closure, and in-space biomanufacturing for sustainable space operations.[4] Using alternative feedstocks for microbes in biomanufacturing, working toward the goal of complete ISRU, is a critical advantage that biological systems offer over traditional chemical or additive manufacturing.

Alternative feedstocks that could be harnessed for biomanufacturing include those produced by human activity that are generally considered waste, for example, carbon dioxide, black and gray water, food waste, and biodegradable plastics. Human waste streams offer rich alternatives for microorganisms to convert into a wide range of useful products. Additionally, other processes generate waste gases that microbial species can use. For example, oxygen production on the International Space Station (ISS) is accomplished by electrolysis of water. The excess hydrogen is vented into space today but could instead be incorporated into closed-loop systems and become microbial feedstocks. Lunar landers and other spacecraft such as orbital hubs will likely generate excess hydrogen, oxygen, and methane from their propulsion systems that could also serve as useful materials for the cultivation of microbial species.

Today, these alternative feedstocks are purged from orbital vehicles and platforms at significant cost. Therefore, it is critical to understand the technological gaps and economic drivers that keep such closed-loop systems and recycling from being fully realized in space environments.

Once biomanufacturing processes are established, waste streams from the fermentation processes become important local resources. Recycling fermentation byproducts, such as the liquid media used to grow microbes, or converting spent biomass into a nutrient source would be another important way to conserve materials for subsequent runs and reduce the amount of launched resources required for space-based biomanufacturing.

There may be additional non–human-sourced resources that can be explored toward a future goal of total ISRU lunar platforms. While regolith is often overlooked as a meaningful feedstock for microbial species due to its lack of carbon, ongoing investigations suggest regolith could act as a source of trace minerals needed for microbial species to thrive.[5] Significant work shows that lunar and Martian regolith could be used to support plant growth as a structural matrix and how plants could derive nutritional value from these soils.[6] However, there are challenges to using regolith in biological systems. For example, although simulated lunar regolith has been heavily used in literature and is a chemical match for the lunar maria, it does not replicate the sharp edges and electrostatic charge of true lunar regolith, which may have significant impact on the bioavailability and cellular toxicity for living systems.[7]

20.3 Space Conditions and Challenges for Microbes

The physical properties of space and spaceflight are uniquely harsh on Earth-evolved biological systems. The survival and reliability of microbial strains for in-space biomanufacturing capability are not fully understood. Specifically, microgravity and galactic cosmic rays (GCR) have unpredictable effects on a microbe host strain and its native or engineered metabolism. Their levels of intensity vary tremendously depending on the location in space, requiring evaluation of microbial strains at multiple relevant gravitational and radiation levels.

20.3.1 Partial Gravity

To study the microbial effects of variable gravity on Earth, partial gravity can be simulated by using rotating wall vessels (2D clinostat) or random positioning machines (3D clinostat).[8] Proponents argue that the average vector of gravity that the cells experience can be set to zero or other fractional gravity conditions. Detractors point out that while this may be true, at any given point in time they still experience the normal gravitational pull of the Earth.

While both systems may replicate some of the impact of partial gravity, they cannot replicate the lack of thermal convection and absence of mixing present outside Earth gravity. This is important because microbes for biomanufacturing are grown in liquid fermentation vessels, where a lack of mixing can interfere with nutrient distribution and overall production. On the ISS, for example, diffusion is the only source of movement of molecules. These factors are challenging to replicate terrestrially.

Recent results contend that the only way to truly study partial gravity is to conduct the experiments in spaceflight.[9] Such testing has shown that multiple biomanufacturing strains exhibited significantly different growth, production rates, and gene expression via RNA-seq when tested on the ISS compared to simulated microgravity.

20.3.2 Galactic Cosmic Radiation

No natural GCR reaches the surface of the Earth, but microbes will be exposed to varying amounts of radiation, which will result in variable biological function. NASA's Space Radiation Laboratory at Brookhaven National Laboratory was built specifically to carry out radiobiology studies and offers the only state-of-the-art GCR simulation.[10] However, the beam configuration was designed to replicate GCRs at the energy levels that would affect astronauts under very specific conditions, namely, shielded from the space environment by a spacecraft or similar habitat. It is unclear how the short timeline of the exposure in model systems would compare to the longer, cumulative timeline of long-term space conditions.

More accessible radiation sources include x-ray and cesium sources. These do not accurately replicate the heavy ion species found in GCR, often cannot produce high enough linear energy transfer to simulate GCR, and are in large part not equipped to facilitate biological studies. Recent studies indicate differences in growth, production rates, and gene expression by multiple biomanufacturing production strains exposed to different levels and types of simulated GCR on Earth.[11] These results provide insights regarding adaptability of these strains to radiation and a path forward for engineering microbes for space conditions but must be compared to results from in-space experiments to determine relevancy to lunar and space biomanufacturing.

20.3.3 Water

Water is the solvent of all biological processes. In the austere space environment, technologies to extract water from the lunar surface or recapture water vapor from human habitats will be critical to achieve closed-loop biological systems.[12]

20.4 Potential Economic Use Cases for Biomanufacturing on the Lunar Surface

NASA and DARPA are actively investigating biologically produced materials and products produced in space as well as how production organisms can be engineered to excel in the space environment. In this section, three potential economic use cases for lunar biomanufacturing are discussed: recycling, biomining, and infrastructure.

20.4.1 Recycling

Some high-value biological production processes have been demonstrated in space, like protein therapeutics that form smaller and more uniform crystals.[13] However, the more transformative use case of biologically produced materials is very different from current terrestrial profit margins calculated for products made in space. For example, the ISS produces a vast amount of trash in the form of human waste, plastic and paper wastes, and consumable products. All of this must be brought back to Earth or burned up on reentry. Biological reduction or upcycling of the trash on orbital platforms or the lunar surface could free up more cargo space, reduce the number of launches required, and contribute to a positive economic ecosystem.

For life support, biological systems, microbial species, or plants can consume waste carbon dioxide and produce oxygen. Currently the ISS uses significant energy to scrub carbon dioxide out of the cabin atmosphere. Biological systems could reduce this burden, contribute to reduced power requirements, and produce oxygen as a byproduct. These examples demonstrate significant additive economic and logistical value to orbital hubs or a lunar habitat.

20.4.2 Biomining

As a lunar ecosystem is developed, minerals and metals will be necessary for construction, infrastructure, and manufacturing. For terrestrial use cases, metal mining relies on high density ore to be economical. However, lunar regolith is extremely fine and elementally dispersed. Terrestrial methods are not as competitive or efficient.

Using microbial systems to obtain specific elements from raw ore is actively used on Earth for high-value trace elements like copper, uranium, nickel, and gold.[14] Microbial systems have been considered for use on the Moon, Mars, and asteroids to extract valuable material for in situ construction and manufacturing.[15] This is because biomining offers significant advantages over the extremely high energy and power systems where regolith is liquefied and elements are separated. Microbial species can extract specific elements with high selectivity, at normal pressures and temperatures, without harsh chemical solvents or high energy demands. Most critically, biology is excellent at extraction from low-grade ore like lunar regolith. Since purified metal products are not carbon-based, the process can be run on little to no additional feedstock once initiated, by exploiting carbon recapture from the system. Engineering microbes to function in the unique lunar environment, and lunar prospecting to determine locations where biomining presents an economic advantage over traditional mining, are the first steps in developing bio-assisted regolith mining strategies. This has been proposed as one of six key hypotheses to accelerate the lunar economy.[16]

20.4.3 Infrastructure

Regolith will be a critical building block for lunar constructions and infrastructure.[17] Biology offers a novel alternative manufacturing paradigm, whereby the binder materials used to glue the regolith together are made locally from alternative waste streams. Materials such as biopolymers have shown significant promise as regolith binders to enable construction on the lunar surface.[18]

20.5 Conclusions

The ability to sustainably produce molecules and materials via biomanufacturing and leverage biology for sustainable closed-loop systems could provide integrated solutions for a human presence on both orbiting hubs and the lunar surface. Predictive models and technoeconomic projections of the space economy will help determine the conditions under which biomanufacturing could play a role in this ecosystem. This includes projected trade-offs, costs, or logistical dynamics under which space-based biomanufacturing offers advantages over synthetic chemistry, additive manufacturing, or launching terrestrially manufactured materials.

However, significant open questions remain on what technoeconomic models may specifically address. What technologies are required to fill the gap between now and a future where the Moon is economically viable? Whose role is it to develop those technologies?

A sustained human presence in space and a sustainable lunar ecosystem will need cost-effective technologies that do not depend on constant resupply from Earth. As humankind ventures farther and stays longer in space, ISRU and biotechnology approaches, including biomanufacturing, will be essential for ensuring the LunA-10 vision comes to fruition and can act as asymmetric enablers for cases that may only be economically viable with the help of biology.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Cockell, "Bridging the Gap."
2. "When a court hears a case 'de novo,' it is deciding the issues without reference to any legal conclusion or assumption made by the previous court to hear the case." Cornell Law School, "De Novo," accessed December 4, 2023, https://www.law.cornell.edu/.
3. Santomartino et al., "Toward Sustainable Space Exploration."
4. National Academies of Sciences, Engineering, and Medicine, *Thriving in Space.*
5. Unpublished results from the DARPA B-SURE program, "B-SURE: Biomanufacturing: Survival, Utility, and Reliability Beyond Earth," n.d., https://www.darpa.mil/.
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7. McKay et al., "JSC-1: A New Lunar Soil Simulant."
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13. Reichert et al., "Pembrolizumab Microgravity Crystallization Experimentation," 28.
14. American Geosciences Institute, "What Is Biomining?," https://www.americangeosciences.org/.
15. Santomartino et al., "The Smallest Space Miners."
16. Nayak, "Six Hypotheses to Accelerate a Lunar Economy."
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21

The Role of Insurance in the Commercialization of the Moon

David Jonas and Alison Wynne[1]

20.1 The Insurance Landscape for Space Ventures

The dawn of a new era in space exploration and commercialization is upon us, with ambitious plans to establish a self-sustaining economy on the lunar surface. This *Field Guide* discusses several innovative efforts to create infrastructure that supports permanent settlements and economic activities. However, one critical aspect that remains a significant barrier is the challenge of insuring these private ventures, especially given recent statistics that indicate an associated high risk.

In 2023, the insurance industry faced a sobering reality: companies operating in space experienced losses that *surpassed the total premiums collected*. The total claims made by space-related enterprises exceeded $800 million, while the total premiums collected amounted to approximately $600 million. This imbalance was driven by a series of high-profile failures and the intrinsic risks associated with space missions. As a result, many insurers are reluctant to underwrite such high-stakes ventures.[2] This shortfall highlights the financial precariousness in this burgeoning industry as well as the significant risk insurers take on, revealing implications for the Exploration Age and Foundational Age of a future lunar economy.

20.2 Shifting Risk Profiles from Orbital to Lunar Missions

Current insurance risk profiles for orbital spacecraft are already stringent, with considerations for launch failures, satellite malfunctions, and space debris impacts. For lunar missions, the complexity and risk factors multiply, as unique challenges must be considered:

- **Harsh environment**. The Moon's surface presents extreme temperatures, micrometeorite impacts, and intense radiation, which can damage equipment.
- **Distance and communication**. The greater distance and (in some cases) no direct line of sight to Earth complicate real-time communication and remote control, increasing the likelihood of mission-critical failures.
- **Non-return missions**. Infrastructure intended to stay on the lunar surface poses additional risks. Unlike traditional satellite missions that have finite operational periods, these missions involve maintaining functionality and safety indefinitely.
- **Jurisdictional issues.** The lack of a clear legal framework for activities on the Moon complicates liability and insurance claims. The Outer Space Treaty of 1967 does not adequately address commercial activities, creating uncertainties about jurisdiction, property rights, and regulatory responsibilities.

From an insurance perspective, these factors translate into higher premiums and more comprehensive policies that need to cover a broader array of potential failure mechanisms. Traditional space insurance models primarily focus on launch and operational phases in Earth's orbit. These must evolve to address the prolonged and varied risks associated with lunar operations.

This will naturally have an impact on insurance premiums. Quantifying this impact is challenging due to the nascent nature of lunar missions and the highly variable factors involved. However, expert estimates by the authors suggest that premiums for lunar surface missions could be an *order of magnitude higher* than those for orbital missions. For instance, while typical insurance premiums for satellite launches range from 5 percent to 15 percent of the satellite's value, premiums for lunar missions could range from 30 percent to 50 percent of the mission's value, reflecting the increased risk and uncertainty.

20.3 Implications of High Premiums to a Future Lunar Economy

To mitigate high premiums, several solutions could be implemented:

- **Pooled risk mechanisms**. By pooling resources, spacefaring entities can spread the risk, potentially lowering individual premiums. This approach might reduce premiums by 10 percent to 20 percent, as the risk is distributed across multiple stakeholders.
- **Government backing**. Government-underwritten insurance, particularly early in infrastructure development, could provide a safety net, encouraging insurers to offer coverage at lower rates. This backing could halve premiums, bringing them closer to the current range for high-risk orbital space ventures.
- **Technological advancements**. Improvements in technology directly reduce the risk of mission failures. For example, advancements in autonomous systems and better radiation shielding could reduce premiums by up to 30 percent, as these technologies enhance the reliability and safety of lunar missions.

The commercialization of space and the establishment of a lunar economy represent the next giant leap for humankind. However, the high-risk nature of these missions, highlighted by recent financial data, poses significant challenges for the insurance industry.[3] Without adequate risk mitigation strategies, the financial viability of lunar ventures remains uncertain. Insurers and space companies must collaborate to develop policies that balance risk and reward, enabling humanity to extend its economic activities beyond Earth and into the cosmos.

As we transition from orbital to lunar missions, risk profiles will change, requiring innovative approaches to insurance. By addressing these challenges head-on, we can pave the way for sustainable economic activities on the Moon and beyond, ensuring that the final frontier is not just a dream, but a thriving reality.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Authors Jonas and Wynne are from Brown and Brown Inc.
2. Slingshot Aerospace, "State of Satellite Deployments and Orbital Operations: 2023 Report," April 30, 2024, https://www.slingshot.space/.
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Lunar Interoperability Standards with the LOGIC Consortium

Edited by Michael Nayak[1]

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22.1 The Importance of Interoperability to a Shared Lunar Future

The world is sitting on the cusp of a resurgence and expansion of lunar exploration, and the complexities involved clearly demand an interdisciplinary approach. The development of fundamental infrastructure systems opens new challenges in lunar technology development, ranging from engineering solutions for sustainable habitats to understanding the biological implications of long-term lunar habitation. The previous chapters laid out some of these perspectives, from planetary science, engineering, biology, and robotics to finance, law, and insurance. This chapter assembles an unbiased evaluation of the key elements of an interoperable ecosystem for lunar exploration, science, commerce, and safety.

Interoperability has been a priority called out by the community since the inception of NASA's Lunar Surface Innovation Consortium (LSIC); this desire is further reflected in policy and strategy documents such as NASA's Moon-to-Mars Objectives. Interoperability can prevent vendor-lock, create cost-effective solutions, and fuel a diverse industrial base as well as facilitate infrastructure and hardware upgrades, maintenance, and repairability. The creation of standards for lunar interoperability will enable a new sector of the lunar economy, promote the creation of new business and jobs, and allow new companies to rapidly join and interface with legacy lunar players and existing infrastructure.

Decisions being made now will affect our progress toward a robust lunar economy and the development of interoperable foundational technologies that underlie it. The foundational elements include resource utilization, technological innovation, international collaboration, and economic sustainability. The need for understanding interoperability considerations in these areas was the impetus for the founding of DARPA's Lunar Operating Guidelines for Infrastructure Consortium, or LOGIC.[5]

22.2 Lunar Operating Guidelines for Infrastructure Consortium (LOGIC)

22.2.1 History and Vision

LOGIC was set up to use community-driven consensus to develop the norms, guidelines, and standards that will support lunar interoperability. Beginning in tandem with LunA-10 and continuing past it, LOGIC aims to enhance development of shareable, scalable, resource-driven, and jointly operated systems. Through its volunteer-based international consortium, LOGIC offers an avenue for participants across government, industry, and academia to pool their insights and create monetizable, mass-efficient services for future users.

DARPA has a history of creating collaborative standards recommendations. The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) began as a DARPA initiative to empower a robust space economy by developing standards recommendations for on-orbit satellite servicing operations and in-space assembly, servicing, and manufacturing. Today, CONFERS is a completely independent body divested from DARPA and run by its own community. CONFERS has transitioned to a dues-based membership open to the global community. In addition to developing industry-led recommendations for standards, CONFERS engages with governmental legislative and regulatory bodies on policies and oversight of satellite servicing activities. The CONFERS model—to build a common understanding across stakeholders, while protecting financial and strategic interests—is directly relevant to NASA and DARPA's goals for a future lunar economy.

Today, LOGIC is motivating and accelerating time-critical, consensus-driven decisions for standards recommendations for technology development with interoperability-in-design for the lunar surface. Developing repeatable methodologies for identifying critical interoperability requirements ensures future innovations have a reliable path for infusion and adoption.

22.2.2 Working Groups

At the time of this writing, the consortium has completed its first year. Three working groups have been stood up, focusing on use cases, standards identification, and standards development for (1) power; (2) positioning, navigation, and timing (PNT); and (3) communications. Future working groups may cover topics such as transit/mobility, environmental impact, robotics, recyclable-ISRU (Re-ISRU), or digital networks infrastructure and incorporate short sprint challenges to create technical tools that further interoperability. LOGIC is designed to be community driven, and, thus, formation of its working groups is determined by community needs.

All focus areas within LOGIC include considerations for market analysis. For example, what does resource sharing look like as a business case? How does a power provider manage power transactions from multiple users and customers? LOGIC explores what these business transactions might look like from an engineering perspective. Rather than focusing on a single function of, or interface between, multiple systems, LOGIC is charged with establishing and standardizing interfaces across the broad future lunar ecosystem.

22.2.3 Participation

LOGIC leverages the expertise and diverse insights of government, industry, academia, and like-minded nations to make the Moon an interoperable ecosystem for peaceful coexistence of infrastructure elements. Decisional outcomes are shared as broadly as possible, leveraging public forums such as LSIC, LOGIC working groups, and website publications.

LOGIC continues to grow in membership as the working groups share their findings. As of January 2025, LOGIC has over 1,000 participants representing 393 institutions and forty-four countries. This includes thirty-six US states and the District of Columbia. Most members (49 percent) are from industry, followed by government (21 percent), academia (15 percent), and nonprofits (11 percent).[6] LOGIC industry members are majority US based (88 percent), with some international (12 percent) industry participation. Traditional aerospace companies, start-ups, and small/medium/large companies are represented. A large contingent of previously terrestrial-only companies is providing insights and expertise for translational technology development in broad engineering, mining, electronics, architecture, and robotics.

Academic members represent seventy-four institutions, 75 percent US based and the remainder international. Australia, Canada, Finland, France, Germany, Luxembourg, Pakistan, Spain, Sweden, Taiwan, and the United Kingdom are represented. Academic institutions range from public to private and large to small.

Government-affiliated members represent thirty-two entities. Foreign space agencies such as the Australian Space Agency, Canadian Space Agency, Centre National d'Etudes Spatiales, Egyptian Space Agency, European Space Agency, and Japan Aerospace Exploration Agency are also represented. Other US government agencies represented include DARPA, the Department of Defense, National Geospatial-Intelligence Agency, US Geological Survey, US Naval Observatory, and the Department of State.

LOGIC members include ninety-three nonprofit organizations. Approximately 9 percent are based outside of the United States, in Canada, Greece, Italy, Norway, Russia, and Spain. Domestically, half of the nonprofit members are from the Johns Hopkins Applied Physics Laboratory, which leads LOGIC on behalf of DARPA.

Members of the consortium typically participate in one of three ways:

1. As part of an elite group of volunteer experts who perform technical lead roles and work outside of regularly scheduled meetings
2. As attendees to regular LOGIC meetings to provide feedback, or
3. As participants in technical information-gathering sessions for the three active working groups.

This is expected to evolve and diversify as the consortium begins to propose implementable standards or technical challenges.

22.3 A LOGIC-al Technical Approach

As its acronym implies, LOGIC leverages a logical approach to interoperability, starting with a welfounded systems-engineering perspective. LOGIC methodically develops requirements from end-user needs and use cases and then evaluates whether those requirements align with an existing or emerging solution. The inclusion of stakeholders from commercial companies, academia, international partners, and government organizations allows a diverse set of use cases to answer the important question: "How can you plan for interoperability on the Moon, with whom, and for what?"

To develop lasting standards, it is critical to engage diverse perspectives and leverage existing standards. That is the fundamental basis of LOGIC's approach to standards, summarized as "adopt, adapt, author."

22.3.1 Adopt, Adapt, Author

"Adopt, adapt, author," in that order, represents the most cost-effective financial investment and shortest delivery time to achieving interoperability:

- **Adopt**. If an existing standard completely satisfies an interoperability gap, that standard is adopted as is and added to the LOGIC standards profile.
- **Adapt**. If an existing standard nearly satisfies an interoperability gap, advocate to adapt the standard with the standards development organization (SDO) and contribute technical expertise for those adaptations and updates.
- **Author**. If no standard exists to satisfy a critical interoperability gap, identify and advocate to an SDO aligned with the technical need to author a new standard, and contribute technical expertise to its development.

Authoring new standards could have long delivery timelines that are slower than the development pace of technologies that would use that standard. While this is not ideal, LOGIC presents a reasonable entry point for consensus-driven development of such standards, where gaps are identified.

22.3.2 Deriving Use Cases and Requirements

What interfaces matter, and what standards might be needed? LOGIC answers these questions through community development of use cases. A use case is a list of actions or event steps, typically defining the interactions between a user and a system, to achieve a goal. To bound the scope of a use case, one begins by writing a user story in this format: "As [a user], I want to [perform this action] to [accomplish this goal]." This use case is then described with narrative and sequence diagrams, activity diagrams, or use case diagrams.

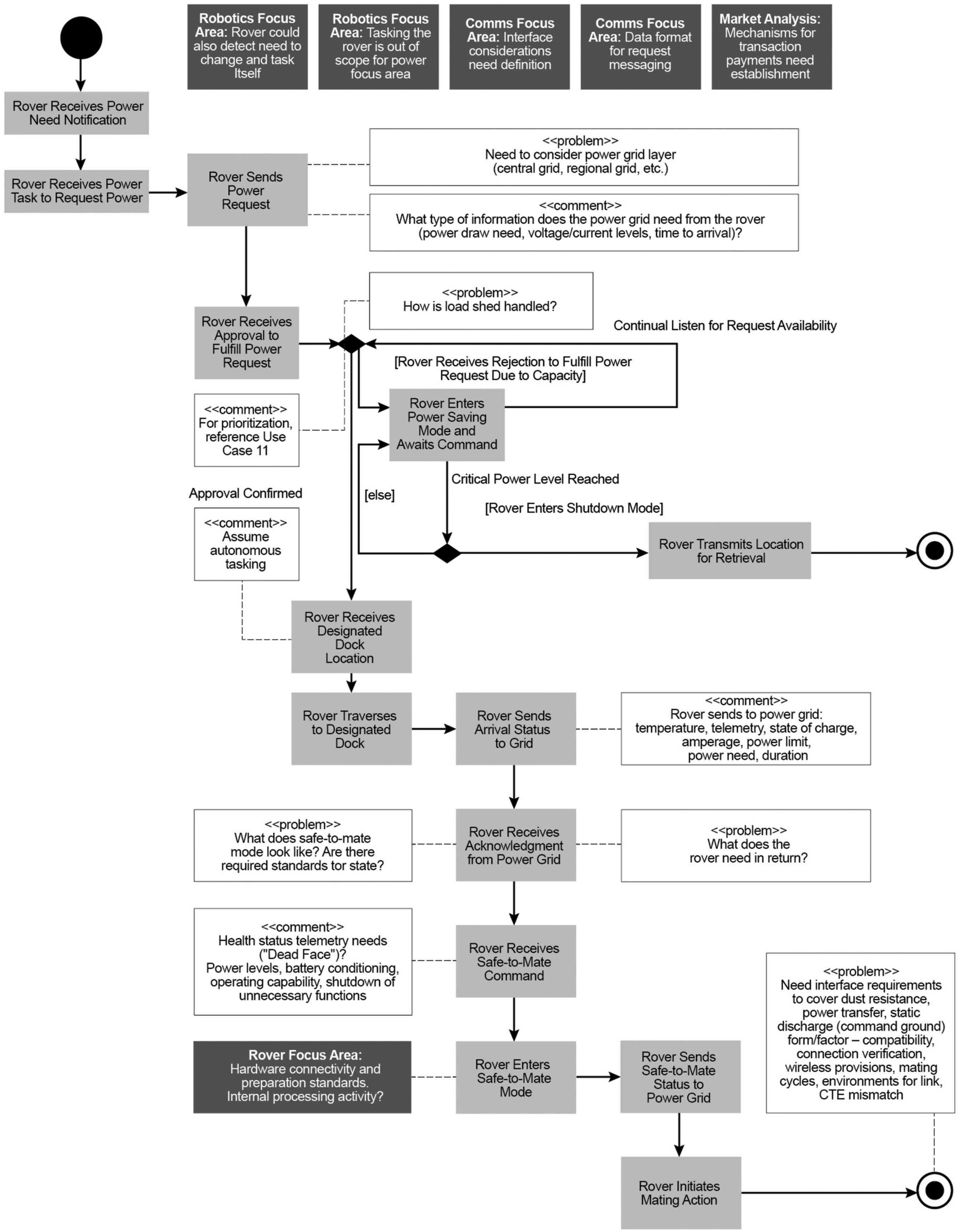

Figure 22.1. Example of rover use case activity diagram developed within LOGIC

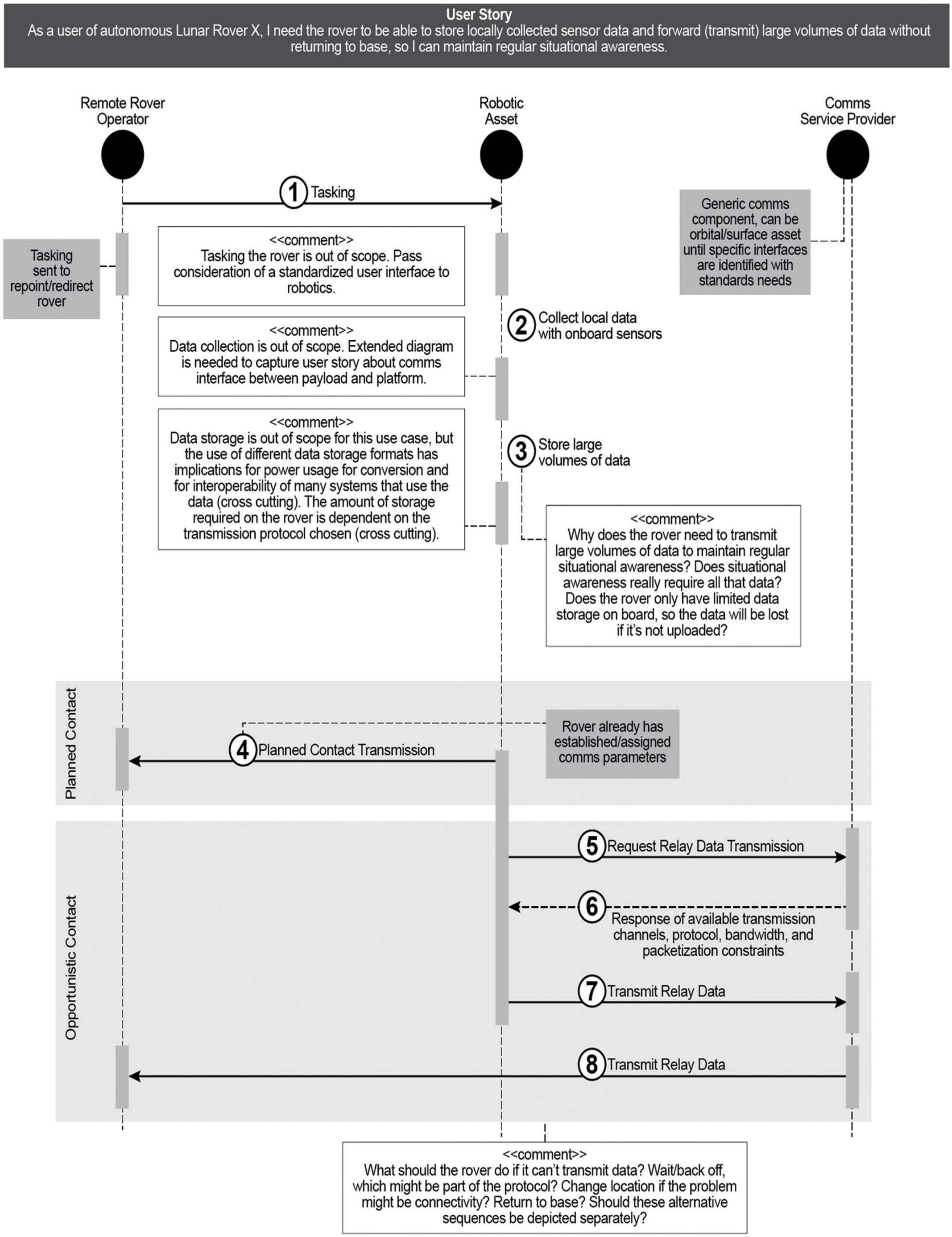

Figure 22.2. Example of a sequence diagram developed within LOGIC

By clearly articulating user needs and use cases, LOGIC's working groups derive requirements and identify interfaces that enable interoperability. Figure 22.1 shows an example LOGIC use case where a lunar rover can identify its location relative to a charging station within a regional power grid. The rover then tasks itself to navigate to this location and charge itself for its next mission.

To analyze this scenario, the relevant LOGIC working group (power) first identifies end-user needs then deconstructs them into tangible and workable pieces for analysis. In a working group meeting, participants discuss and document individual actions via use-case narratives and visualize them using model-based systems-engineering tools. One example of interoperability requirements is the need for hardware compatibility between a rover and power grid system, such that the rover can safely mate to a charging station without causing harm to the entire power grid, and vice versa.

Through technical discussions, working group members define what "safe to mate" means on the Moon. This may include considerations for connectors in dusty environments and fault protection on both the rover side and power grid side. Working group members are encouraged to look at the problem holistically and discuss hardware compatibility, interoperability of communication systems, data format, monitoring or telemetry information exchanges, and other relevant factors.

Figure 22.2 depicts a sequence diagram for a use case where an autonomous lunar rover needs to be able to collect and transmit large volumes of data to its base. At a micro level, sequence diagrams are useful in depicting communications and interactions between blocks in sequential order and are intended to drive design efforts. Sequence diagrams are a powerful tool for LOGIC because consortium members can understand the interactions between subsystems of a future scenario, spurring discussions on interoperability.

22.4 Standards Fundamentals

The US Office of Management and Budget states that all federal agencies must use *voluntary consensus standards in lieu of government-unique standards* "in their procurement and regulatory activities, except where inconsistent with law or otherwise impractical."[7] These are developed or adopted by voluntary consensus standards bodies and include provisions requiring owners of relevant intellectual property (IP) to make that IP available on a "non-discriminatory, royalty-free or reasonable royalty basis to all interested parties."[8]

In parallel with identifying interoperability requirements, LOGIC works to identify existing industry standards applicable to lunar missions. Once interoperability requirements are identified, they are then mapped to existing industry standards to determine whether gaps exist.

The term "standard" is used to refer to different levels of completeness and formalization of specifications. There are generally two types of recognized standards: de facto ("in practice") and de jure ("by law"). De facto standards govern commonly used technologies or protocols. One example is a Microsoft Office document format, which is not developed by a recognized SDO. De jure standards are developed by SDOs with legal and recognized standing.[9] In the United States, de jure processes are driven by external factors such as antitrust laws. LOGIC leverages existing de jure standards as much as possible.

Overall, LOGIC recognizes that:

- standards are driven by the market, since standards enable competition, which frees buyers from being locked into a single vendor;
- standards development requires people committed to the value of the standard, by contributing time, infrastructure, and process; and
- while everyone wants an efficient, responsive standards process, that must be balanced against delivery of complete, accurate technical content.

22.5 Summary of Existing Standards

LOGIC's first task was to gather existing standards to provide a basis for its adopt, adapt, author approach,[10] focused on the existing power, communications, and PNT working groups.

Existing power standards address areas such as modular electronic development for space power systems, quality requirements for electrical components in space, safe use of batteries in space, quality requirements for space solar cells, power quality for international space power systems, and others. However, many of these standards are only applicable to closed-loop spacecraft systems rather than a scalable power network. Most standards recommendations for power will likely fall under the "adapt" approach; for a subset of standards, LOGIC is compiling recommendations for the creation of addenda for lunar power system applications.

Communications and PNT standards are relatively more mature than others, since these services are inherently based on interoperability. Organizations like the Consultative Committee for Space Data Systems have successfully developed communications and data systems standards for spaceflight. However, the environment has a heavy impact on what terrestrial technologies can be applied to lunar missions. Positioning and navigation on the lunar surface depend on accurate mapping abilities, and standards do not yet exist to include mapping projections and reference systems.

Figure 22.3, another output from LOGIC's toolbox, contextualizes a communications and PNT block definition diagram and notional mapping of standards to block elements. Mapping of interface and interoperability requirements to existing standards will be largely manual and relies heavily on the collective knowledge of consortium members. LOGIC is exploring the possibility of automating and optimizing this mapping effort using large language modeling, to quickly parse through hundreds of pages of standards and identify applicability to derived interface requirements for use-case analysis.

LunaNet, NASA's interoperability specification framework, is tasked to identify the Lunar Reference System (LRS) and the Lunar Time System Standard (LTC), not yet released. The White House Office of Science and Technology Policy has officially directed NASA to create a unified time standard for the Moon by the end of 2026.[11] While LunaNet is a start, it is being developed primarily to support NASA's Artemis missions, particularly in the south pole region. This is a limited scope when compared to the broader needs for a sustained commercial presence anywhere on the Moon.

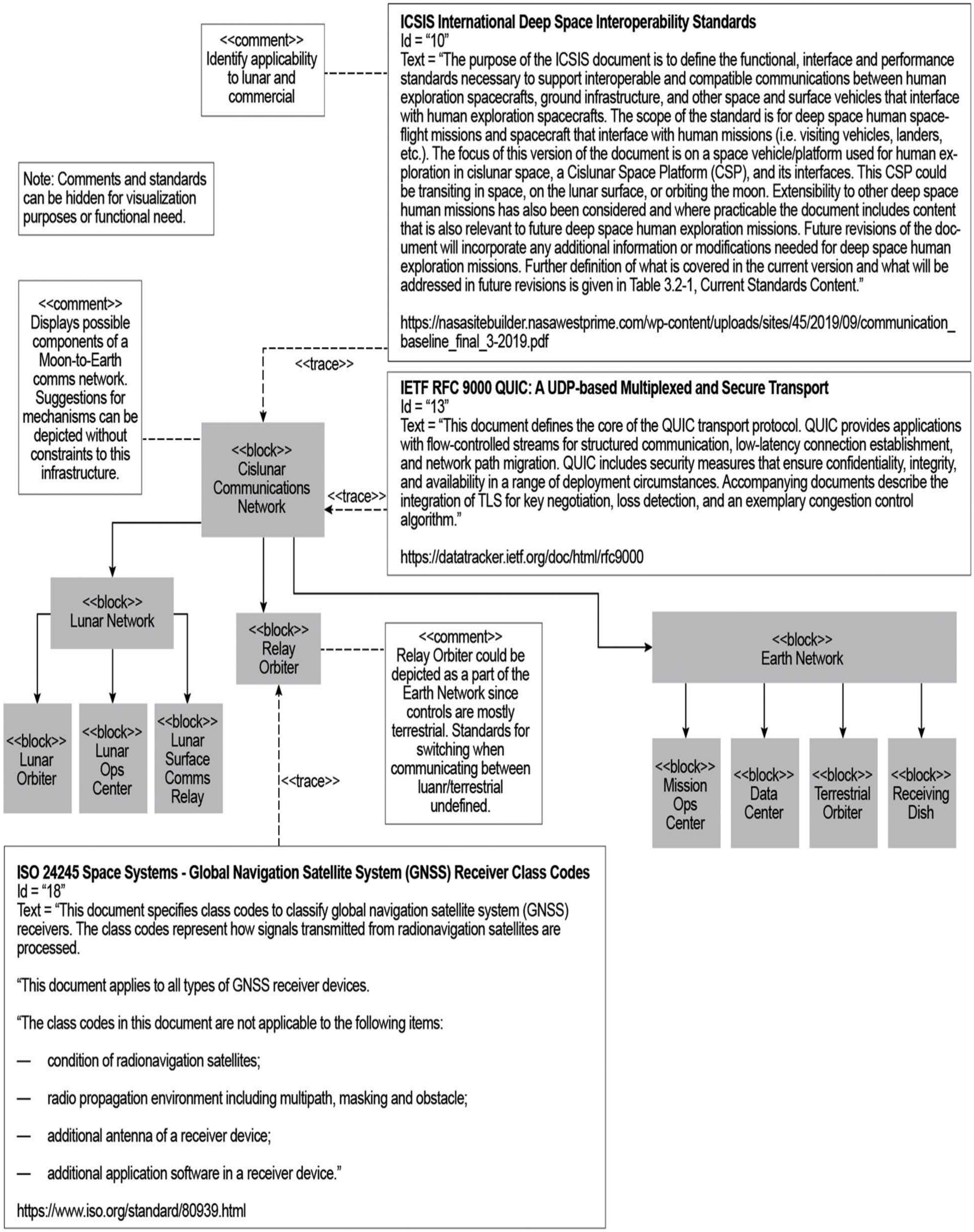

Figure 22.3. Communications and PNT block definition diagram and notional mapping of standards to block elements

22.6 Looking Ahead: Laying a Standards Foundation for a New Lunar Era

In 2023–2024 alone, three countries successfully placed hardware on the lunar surface. Each of these systems required its own power supply, communications infrastructure, heat management, and other critical subsystems. If standard, interoperable power supplies and communications infrastructure were already on the surface, significant additional capability would be unlocked for those missions. Infrastructure providers would have economic incentives to work together on these systems, making a sustained presence on the Moon possible and profitable earlier.

In the long term, creating an ecosystem that is economically viable, interoperable, and capable of maintenance and growth is critical to the success of a commercial lunar economy. A plethora of near-term missions, infrastructure plans, and capability studies drive the need for standardization at the framework level. Electrical, transportation, and communications infrastructure enables critical economic functions on Earth; the same will be true on the Moon. Interoperable technologies and standards can deliver sustainable infrastructure payloads to the lunar surface and vicinity, and LOGIC is making initial strides in this direction.

Notes

(Notes are presented primarily in shortened form. For full information, see the relevant entry in the bibliography.)

1. Defense Advanced Research Projects Agency (DARPA).
2. Blue Sky Innovators (in support of DARPA).
3. Authors Meidenbauer, Arcido, Clyde, Fuhrman, Jaburek, Morse, Mortensen, Shin, and Vigil are from Johns Hopkins Applied Physics Laboratory.
4. Mach 20 (in support of DARPA).
5. For additional details, see LOGIC, https://logic.jhuapl.edu.
6. Four percent of LOGIC members cited their affiliation as "other."
7. Office of Management and Budget, "Circular No. A-119 Revised."
8. Office of Management and Budget. A voluntary consensus standards body is defined by the following attributes: (1) openness, (2) balance of interest, (3) due process, and (4) an appeals process.
9. Some examples of SDOs are the Institute of Electrical and Electronics Engineers (IEEE), the International Organization for Standardization (ISO), the American Institute of Aeronautics and Astronautics (AIAA), and the Simulation Interoperability Standards Organization (SISO).
10. Standards surveyed came from these institutions: AIAA, ISO, American Society for Testing and Materials International (ASTM), NASA, SAE International, International Deep Space Interoperability Standards (ISPSIS), International Electrotechnical Commission (IEC), US Department of Defense, Wireless Power Consortium, Space Frequency Coordination Group (SFCG), Interagency Operations Advisory Group (IOAG), and Consultative Committee for Space Data Systems (CCSDS).
11. Jeff Foust, "White House Directs NASA to Develop Lunar Time Standard," SpaceNews.com, April 2, 2024, https://spacenews.com/.

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Next Steps for the Commercial Lunar Economy

Jay Raymond

John (Jay) Raymond is a retired four-star US Space Force General who was the first Space Force "Guardian" and served as the first Chief of Space Operations. For his work in leading the initial standup of the Space Force, he has been described as the "father of the Space Force."

In December 2023, I was at the Kennedy Space Center in Florida to observe a Falcon Heavy launch of a Space Force X-37b Orbital Test Vehicle. I have been on console for many space launches over the years and have observed countless others. But that night was memorable, not only because of the successful launch of an important capability, but also because of the backdrop, a full Moon.

Launch Pad 39A was the same launch pad used to launch astronauts Neil Armstrong, Buzz Aldrin, and Michael Collins on the first crewed mission to the lunar surface. Looking out at Pad 39A and seeing a bright full Moon in the night's sky as a backdrop was surreal. It immediately brought me back to the living room floor of my childhood home in West Point, New York, where I sat watching the telecast of Neil Armstrong taking his historic first step on the Moon.

For a young boy, the excitement of space exploration and science surrounding the Apollo mission was enough to propel me toward a career in space. However, as the First Chief of Space Operations for the United States Space Force, I came to appreciate the Moon meant so much more to our nation and to the world.

Space as a global domain enables us to build vast global partnerships. A case in point is the Artemis program. Even when countries may have conflicts here on Earth, their space programs have allowed them to put those differences aside and partner for the good of humanity in space. In the future, as you've read in this *Field Guide*, the Moon can become the center of a new space economy, providing United States industries with opportunities in mining, tourism, and infrastructure development. It has recently been speculated that the first trillionaire will be the someone who mines minerals from the Moon and returns them to Earth.[1] The Moon contains valuable natural resources, including elements that are rare on Earth, such as helium-3, a potential fuel for future nuclear fusion reactors.

What was once a domain reserved for nations is today accessible by high school students. Technology that was historically being developed and advanced by the governments is now being paced by commercial industry. As we move into this new lunar era, we do so knowing the space domain has changed significantly, largely due to commercial space and the reductions in the barriers to entry into the domain.

As stated, DARPA LunA-10 attempts to "chart a path towards continued international lunar cooperation with responsible, peaceful and sustainable exploration." The program solicitation goes onto posit, "Can we create and foster the conditions that cooperation will contribute to the development of mutual understanding of friendly relations between states and people as envisioned by the Outer Space Treaty?"[2] The answer to that question is simple: *we must*.

How we do so is difficult and will require bold and forward-looking leadership from the United States. This will mean strong international partnerships, a robust public-private partnership with commercial industry, and a safety framework to ensure operational success.

The Moon stands as both a mirror to our past achievements and a beacon for future aspirations. As we venture back not just as visitors but as pioneers, we must affirm our commitment to the relentless pursuit of knowledge and ingenuity. A sustained presence on the Moon will allow us to boldly envision a future beyond the limits of our earthly confines. It's time we realized that a sustained presence on the lunar surface will benefit humankind here on Earth while setting the foundation for our future—one where the stars are no longer out of reach and light the way for all of humanity.

Notes

1. Bloomberg TV, "Want to Be a Trillionaire? Try Space Mining," October 21, 2019, https://www.bloomberg.com/.
2. "LunA-10 Exploration Announcement Solicitation," August 15, 2023, https://sam.gov/.

Editor Acknowledgments

Contributions from hundreds of people and tens of thousands of person-hours of work went into making this book possible. As the editor of this compendium, my primary thanks go to all the contributing chapter authors—131 people from forty-eight organizations—who applied their technical expertise and thought to this endeavor. Thirteen visionary companies fought their proprietary instincts to come to the table and work together to craft this vision of the future: Blue Origin, CisLunar Industries, Crescent Space, Fibertek, Firefly Aerospace, GITAI, Helios Project Ltd., Honeybee Robotics, ICON Technologies, Northrop Grumman, Redwire Space, Sierra Space, and SpaceX.

A unique and singular thanks goes to my dedicated Scientific and Engineering Technical Analysis (SETA) support team: they worked harder than anyone to make this vision possible. Lee Pele (business and financial manager) worked three jobs in one most every day and supported me across two DARPA offices. Ashley Batjer put in significant background time and effort during the manuscript editing process to help us deliver a final product. Christie White brought her signature sass and sharp-witted humor to every interaction with our consortium group. Anna Hall was a key pinch-hitter every time we were overwhelmed (we frequently were).

During program execution, I often said that LunA-10 was a "thought experiment backed by analysis." In that way, it was a visionary program in the best DARPA tradition. I'd like to thank all the DARPA team members who made the LunA-10 program, and thereby this book, possible. In particular, I'd like to acknowledge the Strategic Technology front office and security team: Marybeth Barham, Jasmine Mack, Michelle Ajuria, Jamie Bugett, Brian Flavin, Linda Marshall, Rob Newton, Ryan Weed, and Calvin Wakeman. Thanks to the Strategic Technology Office leadership team of Philip Root, Whitney Mason, Donya He, Jessica Marsh, and Nick Haeuptle for backing this project at every turn. The dynamic nature of LunA-10 would not have been possible without acrobatics from the DARPA Contracting Management Office, specifically rockstar contracting officer James "Mac" Ritch, Simon Klink, and our NASA contracting officer representatives: Olive Stohlman, Vianni Ricano-Cardenas, and Sandie Chellis.

The unique and diverse LunA-10 government integration team—the GIT, as we lovingly referred to them—ingested wildly disparate points of view and knitted cohesive frameworks that tied everything together. A huge thanks to Elizabeth (Liz) Hyde, formerly of the US Geological Survey, and Shawn Britton, from NASA Langley, for leading the government team. Thanks also to the other members of the GIT, Stan Straight, Olive Stohlman, Luke Sauter, Daniel Kulp, Katelyn Eppich, Curtis Boyd, and Joshua Daniels, for their academic and intellectual contributions.

A final thanks to the fast-charging publication team at Air University, led by Paul Hoffman and Donna Budjenska. Thanks to Daniel Meidenbauer, Emily Poyourow, and the LOGIC team at the Johns Hopkins University Applied Physics Laboratory for forging that connection.

Envisioning the future is easy. Dragging it into the present and making it real is not. We have our work cut out for us, but it is possible, and the time for action is now. I hope this work inspires you to help us push this rock uphill to the finish line.

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Abbreviations

AE	alkaline electrolysis
AFS	Augmented Forward Signal
ARPA	Advanced Research Projects Agency
ATC	air traffic control
BER	bit error rate
CaaS	Compute as a Service
CBE	current best estimate
CFD	Computational Fluid Dynamics
CIL	customary international law
CLPS	Commercial Lunar Payload Services
COMNAP	Council of Managers of National Antarctic Programs
CONFERS	Consortium for Execution of Rendezvous and Servicing
CONOPS	concept of operations
COPUOS	Committee on the Peaceful Uses of Outer Space
CTE	coefficient of thermal expansion
DARPA	Defense Advanced Research Projects Agency
DEM	digital elevation models
DIABLO	Deployable Interlocking Actuated Bands for Linear Operations
DOR	deoxygenated regolith
DRM	Design Reference Mission
DTE	direct-to-Earth
ECLSS	Environmental Control and Life Support Systems
ECS	Earth Communications System
EIRP	Effective isotropic radiated power
EOL	end of life
EPM	electro-permanent magnets
ESA	European Space Agency
EVA	extravehicular activities
FEC	forward error correction
FIR	flight information regions
FPC	flexible printed circuits
FSP	fission surface power
GCR	galactic cosmic rays
GEO	geosynchronous Earth orbit
HGA	high gain antennas
IAATO	International Association of Antarctica Tour Operators
ICAO	International Civil Aviation Organization
IP	intellectual property
ISRU	in situ resource utilization
ISS	International Space Station

LCT	laser communications terminal
LDC	Lunar Development Cooperative
LEO	low Earth orbit
LION	Lunar Infrastructure Optical Node
LLO	low lunar orbit
LOA	letters of agreement
LOGIC	Lunar Operating Guidelines for Infrastructure Consortium
LOPES	Lunar Oxygen Production and Energy Storage
LOS	line of sight
LOX	liquid oxygen
LPC	Laser Power Conversion
LRS	Lunar Reference System
LSIC	Lunar Surface Innovation Consortium
LSII	Lunar Surface Innovation Initiative
LTC	Lunar Time System Standard
LTV	lunar terrain vehicle
MGA	medium gain antennas
MLI	multilayer insulation
MMOD	micro-meteorite and orbital debris
MPU	Maximum Performance Unit
MRE	molten regolith electrolysis
MSA	McMurdo Sector Area
MUST	Modular User Surface Terminal
MVE	minimum viable experiment
MVP	minimum viable product
NITE	Nighttime Integrated Thermal and Electricity
NOTAM	Notice to Air Mission
NRE	nonrecurring engineering
NSC	National Security Council
NSF	National Science Foundation
OCT	optical comms terminals
ODSP	onboard data storage and processing
OOS	on orbit servicing
OPP	Oxygen Production Plant
OST	Outer Space Treaty
OWPT	optical wireless power transfer
PEM	Proton Exchange Membrane
PEME	polymer electrolyte electrolysis
PEMFC	proton exchange membrane fuel cells
PM	program manager
PNT	position, navigation, and timing

PSR	permanently shadowed region
RaaS	Robotics as a Service
Re-ISRU	recycled in situ resource utilization
RF	radio frequency
RHU	radioactive heater unit
ROI	return on investment
RSG	radioisotope sterling generators
RSGS	Robotic Servicing of Geostationary Satellites
RTG	radioisotope thermo-electric generators
RX	receiver
SaaS	Software as a Service
SAN	Surface Area Network
SBSP	Space-Based Solar Power
SD	signal detection
SDO	standards development organization
SDR	Software Defined Radios
SETA	Scientific and Engineering Technical Analysis
SEZ	Special Economic Zones
SFP	surface fission power
SOE	solid oxide electrolysis
SOEC	solid oxide electrolysis cell
SRL	Systems Readiness Level
SSPA	solid state power amplifier
STM	Space Traffic Management
STN	survive the night
SWaP	size, weight, and power
TRL	Technology Readiness Level
UAS	uncrewed aerial systems
UMIC	universal modular interface converter
UN	United Nations
UNOOSA	UN Office of Outer Space Affairs
USAP	United States Antarctic Program
VMX	vitreous multi-material transformation
WLA	whiteout landing area
YSZ	Yttria-stabilized zirconia

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