# Building with Celestial Bodies

Tim Elrick[1]
*Wentworth Institute of Technology, Boston, MA, 02115*

**The work reflects on how we as architects have chosen to practice throughout history and where it has led us. Recognizing that the life of a building is far more than its completion, a circular approach to design that fully engages known ethical, technological, and economic criteria is desperately needed. Instead of imposing our will upon their surface, Earth, the Moon, and celestial bodies alike must be allowed to inform the way we build. As we are experiencing on Earth, an inherent appreciation and respect for the celestial bodies we inhabit is paramount for mankind's continued existence, otherwise suffering catastrophic consequences. Making full use of what the Moon offers us, the work explores various design processes by hand to prove creating an extraterrestrial habitat entirely in situ is possible. Well aware of the obstacles such a feat poses, the work challenges its reader to deeply introspect on the sacrifice of moral standing for passing pleasures and the devastation said decisions have wrought on Earth.**

## Nomenclature

| | | |
|---|---|---|
| CNC | = | computer numerical control |
| EVA | = | extravehicular activity |
| ISS | = | International Space Station |
| NASA | = | National Aeronautics and Space Administration |
| RLSO | = | Robotic Lunar Surface Operations |

## I. Introduction

In the same way humanity points to caves as the historic precedent of first architecture, so must be our approach to the lunar frontier. In addition, there appears to exist a procrastinative ignorance within humans, overcome only by the severity of the extreme situations we put ourselves in, to turn to powers higher than ourselves for help. This is precisely the case with nature which has become the single-most destructive force of the contemporary era. We, as a people, need to recognize, understand, and accept that nature, and the land we inhabit, is more powerful than we are. Despite the record-breaking tragedies unfolding before our very eyes, there is hope yet. As it turns out, the best defense against nature, is nature.[1] Global climate change and its plague of extreme environments stems from a growing disconnect between man and nature. Aaron Betsky, renowned architecture critic, states that in order to shift the paradigm of humans' ability to effectively engage the Earth, successful projects will, "...find and exhibit the geology, topography, and hydrology of the land along with the layers of human intervention that also shape the ground on which we live and build, producing a history of design transformations that change over time and in relation to natural forces."[2] Engineering the land to restore nature and establish a positive reciprocal relationship between Earth and man is the most effective and utopian form of architecture.[3]

**Image 1. Hellenistic Theatre in Pergamon, Turkey.**

[1] Student, 550 Huntington Avenue, Boston, MA, 02115.

We are only just beginning to see the reality of the land and the state of our relationship with it. Guilt now ravages through much of our culture. Perhaps Betsky puts it best, "We have raped the land as much as we have used it. As we have depleted open space and natural resources, we have left the land scarred, empty, and often poisonous."[4] Recent extreme-weather-related statistics have shattered previous benchmarks, and if we continue down this path, the future is unforeseeably dark.[5] In *Reduction, Reuse, and Recycling on a Future Lunar Base*, Sarah Soliz, Laura Simonds, and Christine Willan team up to assert that as technology has advanced, so has our blatant disregard for the planet.[6] Acting as if the Earth's resources are limitless, such carelessness has led to devastating consequences. By engaging the landscape in a healthy manner, we become more aware of the land we inhabit, physically, mentally, and spiritually becoming one with our planet. This new paradigm for rebuilding and restoring our relationship with the land will yield not only a habitable, but prosperous Earth for all of mankind to enjoy.

Betsky's assessment of our disconnect with and irresponsible use of the land is reinforced by the philosophy that the act of making a building assumes the land we walk on is not enough,

> "Buildings replace the land. That is architecture's original sin. ... What was once open land, filled with sunlight and air, with a distinct relationship to the horizon, becomes a building. The artifices of humans supersede what nature has deposited on a given place."[7]

Once again, our respect for the land is called into question, which in turn manifests the relationship we have with it. One would think that after the relentless destruction wrought by projects solely concerned with doing things quicker and cheaper, that enough would be enough. Unfortunately, the opposite is true. Despite the countless consequences of sacrificing sustainability for immediate gratification, it is our full intention to make the same mistakes on the Moon...and it is not even a question.

A balance between building and land is not only necessary for helping to restore Earth, but setting standards of practice for architecture in extraterrestrial environments. Astrophysicist Chris Impey details in his book *Beyond: Our Future in Space* that we can create self-sustaining habitats using simple technology and available resources. Air, water, and building materials could all be locally generated through this land-centered approach.[8] Globally acclaimed architect Lebbeus Woods' "Underground Berlin" features an underground city whose function is nothing more than to calibrate the energies of the Earth to those of the human body.[9] The concept of becoming one with the world is not new to civilization, but our inability to effectively enact its teachings has put us in a less than favorable situation. Earth is just now becoming aware of the need for change. Thus, implementing such an understanding in an entirely inhospitable environment with which we have negligible experience is a reach to say the least.

The benefits of effectively animating the landscape are limitless. Since the days of cave dwellers, humans have only sparingly made use of nature's geological formations and, therefore, power. Progressions in technology, specifically within structural engineering, now make it possible for humans to engage the terrain in ways previously unimaginable.[10] Caves and tunnels have proven to be humanity's most durable habitations, many still surviving today. The Derinkuyu Underground City is a fitting analog for the Moon as any. Extending to a depth of approximately sixty meters, it is large enough to have sheltered as many as 20,000 people along with livestock and food stores and is a proven example of humans living with the land for extended periods of time. Also in Nevşehir Province, Turkey is Göreme, another proven example of man living harmoniously with nature through its architecture. Dwellings and churches worthy of museum exhibits are carved into picturesque mountain landscapes, offering panoramic views that stretch as far as the eye can see. One cannot help but observe what we are doing to the Earth elsewhere and question how our behavior on the Moon would be any different.

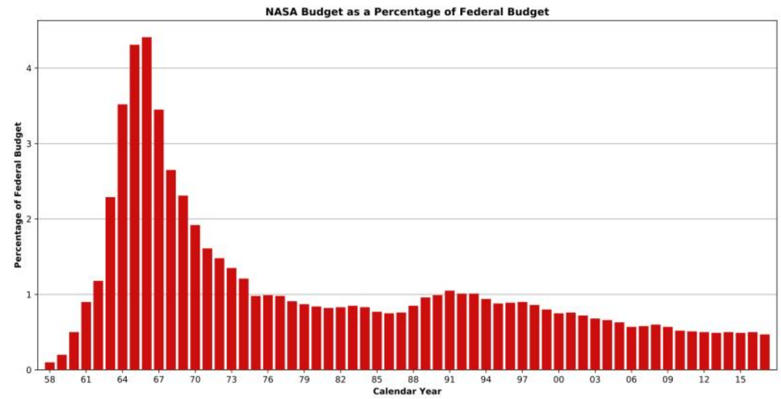
**Image 2. Göreme, Turkey.**

## II. Mission Considerations

*The Prime Directive - Friends don't let friends destroy celestial bodies.*

### A. Setting Context

Public discourse has proven to be the most influential power in terms of dictating the course of human spaceflight. Apollo is a perfect example of this. Graph 1 displays the National Aeronautics and Space Administration's (NASA) comparative funding figures from the time of Apollo until now, representing a nation that rallied behind putting the first man on the Moon. The data shows what it took to achieve such a goal, but also proves why there has not been nearly as big of a headline since. History demonstrates that when society turns its attention and commitment elsewhere, the project remains unfinished.[11] This relates directly to the idea of selling what people want to buy, and in recent years the public has not been buying.[12] The idea of creativity drawn from inspiration is the defining staple of successful human spaceflight initiatives.




**Graph 1. NASA Funding Over the Past Six Decades.**

An anticipated outcome of space travel that is in favor of reestablishing a respectful relationship with Earth would be exposing large numbers of people to what is known as the Overview Effect. The Overview Effect is a perceptual shift documented to happen to space travelers that deepens their appreciation for the fragile nature of Earth. This is said to occur as a result of looking at Earth from outside while experiencing the detached sensation of microgravity, sensitizing travelers to the planetary impacts of human territoriality and environmental destruction while deepening spiritual convictions.[13] There is a lot we can learn from space, but our intention and approach will determine the fruit that is bore. In the words of Apollo 8 astronaut William Anders, "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

The Moon's surface is visible from any point on Earth, and careful steps need to be taken to avoid disfiguring it.[14] Much in the same way that topogeny proves there is a distinct connection between the journey of our ancestors and how we interact with land today, so will prove to be the case with humanity's lunar exploits. The land truly does retain all. Soliz, Symonds, and Willan assert, "(We must) ... address the waste management problems on Earth as they relate to a future lunar moon base and suggest measures to prevent these problems from occurring in this new society. We must take offensive action from the very beginning of settlement so that we will not create problems that will have to be corrected later."[15] Given the vast amount of untouched land offered by the Moon, mankind may be tempted to simply bury trash and other forms of waste beneath the surface.[16] This is just one of the many unethical practices that have backed terrestrial environments into a corner, and establishing such a relationship with the Moon would once again prove to be world ending. It would also show, on the grandest of stages, that we have not learned from our mistakes. Such unprecedented ignorance would solidify a collective succumbing to the clutches of greed and sloth that prevent creative alternative development. By not waiting until the last second to do our best, many of the problems we must now solve on Earth will cease to exist elsewhere.

### B. Criteria

The technology sector essentially dictates what is possible from what is not. This is where program commitments start, financial resources are consumed, schedules are challenged, and, in the end, program legacies are dictated.[17] In 1989, the Boeing Company again addressed the Moon when NASA's Advanced Robotics office commissioned their Advanced Civil Space Systems team to, "...examine options for (and characterize the benefits and challenges of) performing extensive robotic site preparation of planetary base and scientific sites, and lunar and Mars propellant production facilities."[18] This work became formally known as the Robotic Lunar Surface Operations (RLSO) study.

The RLSO study used quantitative end-to-end operations analysis to size base elements, duty cycles, timelines, and construction sequence.[19] Seeking to determine the extent to which mobile robots could streamline and make feasible lunar operations, the rationale that frames this focus is as follows:

> "Permanent human presence on the Moon is challenging to bootstrap. We need facilities on the Moon to support the people, but we would seem to require people to construct the facilities. It is certainly possible to devise incremental operations scenarios to resolve this dilemma, but they require off-nominal circumstances. For example, expecting an initial crew to set up a permanent radiation-sheltered habitat on the lunar surface ... (doesn't) avoid the need for large, strong robots (whether "driven" or autonomous) to do the construction, nor the cost in lunar surface crew time to perform and oversee the task."[20]

Thus, the study proved the most viable method for erecting lunar infrastructure is for assets to be robotically landed, assembled, and operated.[21] Space architecture pioneer Brent Sherwood details vital precepts in his work *Principles for a Practical Moon Base* that must inform the conceptualization and design of lunar work. The first and most fundamental of these is that most lunar base operations, most of the time, must be robotic. An essential component but often overlooked in the design of many lunar bases, this determination is fueled by scope, safety, and economics.[22] Scope includes the near-continuous need for action outside of a habitat, moving large volumes of lunar regolith, and tasks that exceed human capability (e.g. reach).[23] As heavy labor in extravehicular activity (EVA) suits is impractical from a safety standpoint, robots mitigate or avoid potential risks incurred by astronauts.[24] Safety is also considered by reducing risks of construction operations and radiation exposure as well as minimizing unnecessary contact time with the Moon's ever-present hazardous conditions.[25] Being the astronomical expense that it is, a Moon base that sits idle between crew visits is not an economically sound investment.[26] The cost of maintaining a human habitat over time presents another aspect of design to consider and strongly rules in favor of robotics.[27] Therefore, unmanned systems capable of carrying out construction operations and other useful tasks at all phases of a mission timeline adds incredible value to the base as a whole, "The minds and hands of the crew are thus complemented by the strength, reach, consistency, untiring operation, and relative immunity to the EVA environment of machines."[28] This includes realms previously mentioned like crew safety, cost-effectiveness, and productivity, while also enhancing other essential aspects like mission versatility and capability.[29]

Three of the most challenging issues of extraterrestrial design are addressed with a land-based approach: 1. Protection from Radiation; 2. Types of Materials; 3. Overall Costs.[30] Neil Leach is a NASA Innovative Advanced Concepts Fellow that is in the process of developing a robotic fabrication technology capable of printing structures on the Moon and Mars. His assertion is that the future of extraterrestrial construction rests on technologies that utilize in situ materials such as lunar dust.[31] In situ resource utilization is directly related to the "Living off the Land" picture being painted, a cost-effective, feasible design approach with virtually limitless potential both in terrestrial and extraterrestrial domains.

Radiation poses arguably the biggest threat to space missions. The Earth's magnetic field works hard to shield us from lethal doses of the sun's rays, and the lack of such protection on the Moon poses serious danger. Regolith radiation shielding was addressed in the RLSO study by means of a modular, erectable, double-walled vault-shell structure that minimized footprint, transported volume, assembly complexity, and regolith handling.[32] Additional proposals exist that work to use lunar regolith as a natural resource for defensive purposes. Peter Land, architect and designer at the Illinois Institute of Technology College of Architecture, Planning, and Design, presented a shelter design under which a permanent base can be built. Land argues, "Shelter design should minimize exposure in order to maximize the time a person can work outside the shelter."[33] Jan Kipliky and David Nixon of Future Systems Consultants proposed a base entirely shielded by lunar regolith, and E. Nader Khalie of the Southern California Institute of Architecture pushed forth the idea of using lunar regolith for an adobe structure cast in her paper *Magma, Ceramic and Fused Adobe Structures Generated in Situ.*[34]

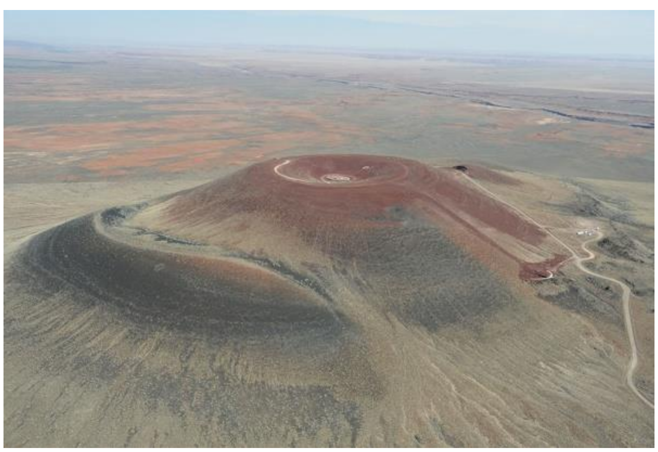


**Image 3. Roden Crater by James Turrell proves harmony can exist between the natural and constructed.**

Above all, human life is at the heart of successful lunar habitat design. With safety a paramount priority, impact from asteroids and meteorites remains one of the deadliest threats home to the Moon.[35] Besides challenges posed by the temperature and humidity conditions of the Moon, the length of a lunar day is approximately fourteen times that of a day on Earth, resulting in significant periods without sunlight to fill robot energy needs if they are to utilize solar power.[36] This makes proper site selection pivotal. Other inhibitors include working in a vacuum, light intensity, uncertainty of water, and the need for robots to be one-hundred percent reliable if they are to operate without a robust maintenance system.[37] Remember, these are just the known factors in an environment that we have little to no experience working with. It is therefore of paramount importance for any serious lunar architecture proposal to establish and be mindful of its criteria list while being flexible enough to change and adapt as needed.

**Image 4. Irish Sky Garden also by James Turrell.**

The extreme, fluctuating temperatures of the Moon will place severe levels of thermal stress on any structure. If not properly handled, said forces will cause the system to fail. Therefore, architecture solely utilizing curves is critical, enabling the form to naturally expand and contract as needed. With a pressurized space having to hold an Earth-like atmosphere, thermal swings will increase interior loads of tension and shear. Corners, as is where these forces will disperse, hold the highest levels of stress, making them vulnerable and therefore undesirable in extraterrestrial settings. Micrometeorites also must be considered through this lens as well. If one were to strike a corner, the chance of it holding are not nearly as high as with a curve where forces would be evenly distributed upon impact. The idealistic lunar forms should accentuate the Moon's unique topographical curves, demonstrating clear intentions to build harmoniously with our celestial neighbor.

A different celestial body requires a different approach to engagement, but the premises of respect and appreciation must remain the same. The Earth is the most poignant, beautiful view in our solar system. As we set a course to renew its face, let our mistakes serve as strong reminders, careful not to ravage the Moon with the same destructive touch. In order to build with new celestial bodies, the following design criteria must be met: use of robots for construction, use of native materials, protection from radiation and micrometeorites, and use of curves to address intense thermal stresses.

## C. Methods

The International Space Station (ISS) set a new precedent of international collaboration for building and operating ongoing, elaborate space infrastructure. To date, the ship boasts five principle space agencies and crew members from eighteen countries.[38] We must learn from what is unfolding: multiple actors pursuing individual interests via unique specialties by means of practical and shared architecture. In a similar way that Soliz, Symonds, and Willan call for the participation of every community member for bases to be fully self-sufficient, so must be our approach to lunar mission design.[39] The peaceful, high-technology international interdependence that the ISS initiated is vital for any future exploits of mankind. We now have the opportunity to advance this precedent in the form of lunar architecture: a luminous symbol of unity and prosperity cast upon the nighttime sky for all to, quite literally, look up to.

The array of large-scale necessities and specialties that come with space can only be supported by an alliance of various nations, one of the many lessons to be learned and applied to Earth. As no single enterprise can bear the full burden of driving all facility requirements, no single use type would dominate the architecture. Tenant diversity provides a robust business base, extracting well-understood terrestrial real estate practices and driving the economic health of spacefaring agencies.[40] It is also able to incorporate the variety of proficiencies and interests that arise with multiple actors. Thus, an international, multicultural approach that accommodates these needs and utilizes the respective strengths of each group is the exact architectural symbiosis needed for optimal results.

The cost of shipping a single brick to the Moon is roughly two million dollars.[41] This would also limit on-site inventory, making additive manufacturing with local soils the preferred option for structure and custom part building.[42] Virtually eliminating transportation costs, 3D printing can both be an essential tool for responsible

Moon-based design and reinforce the premise of "Living off the Land." In addition to safety advantages, the use of 3D printing would allow habitats to be constructed before humans even left Earth, effectively eliminating construction risks and severely reducing radiation exposure.[43] In addition to its widespread availability, the fine-grade composition of lunar regolith makes it a natural choice for lunar tunneling and building operations. It is also a fitting material to 3D print with as it, again, allows us to build with what is already there.[44] Using lunar regolith to the fullest extent will exponentially reduce base building costs and, more importantly, establish a foundation for healthy, sustainable lunar architecture.

Our first step, as architects of the future, is to set clear, ethical intentions, acknowledging exactly why we are doing what it is we are doing. Building on the Moon, or any planet besides Earth for that matter, uniquely situates us as such would be a first for mankind. Therefore, results-based ethics (consequentialism) are to be ignored as there are no prior results to base our decision making on. The ends cannot justify the means because the ends do not yet exist. We are therefore exclusively obligated to act in alignment with the principles of duty-based ethics, the means justifying the ends. Such is the only choice and must be evident not only from our intentions and resulting criteria, but throughout the entire process of creating. Building with the Earth works. Building opposed to the Earth does not. A successful lunar vision will both use the right tool for the job (i.e. robots) and unite a diversity of actors who share an inherent respect for the land in which they dwell. The design research that follows takes the next step, exploring various design processes using the aforementioned methods to shed light on what actual construction could be.

## III. Design Research

### A. 3D Printing

In alignment with a harmoniously balanced cut and fill method of engaging the lunar landscape, only taking what we need, my initial trials worked to discover an approach that allows the Moon to inform the way we build. To maximize technological and economic investment, lunar regolith paired with a 3D printing binder severely reduces mission costs and makes full use of what is readily available. Thus, the ability for a mixture of foam shavings (i.e. lunar regolith) and glue (i.e. 3D printing binder) to execute a layer-by-layer construction methodology with various forms and surfaces emerged as my initial focus.

A clear cut and fill test vehicle was essential for establishing methods that reflected the proposal. The subtractive manufacturing nature of a computer numerical control (CNC) machine most closely aligns with planetary cutting operations. Using a CNC machine, a topographic model was made, the excess foam shavings of which were harvested. These shavings then became part of a foam-glue concoction representative of an extraterrestrial mix of lunar regolith and 3D printing binder. This was a deliberate attempt to emphasize circular design, the waste of one process becoming fruit for the next. Here, the excavated volume is used both as space for underground architecture and building material for aboveground architecture. And so, it was understood that the process of cutting and filling reaches a harmonious balance, simulated by subtractive methods of CNC milling that complemented additive methods of 3D printing.

Upon each form, I carefully extruded the mixture by hand in a similar layer-by-layer manner that my robot would need to for successful construction. Paying careful attention to the design process granted the opportunity to place myself in the position of a robot attempting to extrude material on the Moon. As robots would need to build from the ground up, so followed my hand. As a result, key realizations emerged early during testing that might have otherwise went unnoticed.

**Image 5. Foam-Glue Trial with Inflatable Scaffold.**

An array of failures directed the course of future investigations. First, getting the desired proportion of foam shavings and glue for extruding proved difficult. It became an extensive trial and error process to produce a blend that both extruded smoothly and held soundly. It also raised doubt about using a 3D printing binder altogether. Not only would it contaminate the lunar terrain with a terrestrial substance, directly violating The Prime Directive, but the rapidly fluctuating extreme temperatures of the Moon puts any liquid at serious risk of either solidifying or evaporating. Given the immense cost of any space mission, this is not a risk one should take.

**Image 6. Animated robots portrayed compacting lunar regolith amid a slope far too steep to maneuver.**

Bringing scaffolding, or any support structure from Earth for that matter, also breaks The Prime Directive. Therefore, exclusively using lunar building materials became the heart of this work. To fully engage a mutually beneficial relationship between man and the Moon, making the most of what we have is imperative, a vital lesson to be revived on Earth. Test methods needed to be adjusted to further develop a construction methodology capable of sustaining itself solely with robots and native resources. Through careful inspection of what the robot would be required to do, the need for engineered slopes became clear. Such is not only to ensure robot mobility, but to account for lunar regolith's angle of repose. By going through the process of sculpting the lunar land by hand, simulating robotic operations, and using what might otherwise be considered waste for architecture, a deeper understanding of and appreciation for the project as a whole was had.

Foster + Partners' "Lunar Habitation" inspired the inflatable scaffold membrane I used during these trials. A creative approach for combating the Moon's lethal levels of radiation, covering said shell with material in situ proved tremendously challenging. While the animation used to demonstrate this process is both exciting and aesthetically pleasing, doing so by hand made it clear that vast sums of material will be necessary just to meet minimum coverage requirements. Furthermore, design versatility is limited to bumps on the lunar surface as the material robots layer will also need to become the infrastructure on which they traverse. This aspect is lost in digital demonstration, and without it, while convincing on screen, construction is impossible.

The extraterrestrial designs of tomorrow should not be the same as they were twenty years ago, and yet, for many, this is exactly the case. Such is proof of how we continue to drool over new technologies, as if they can do no wrong, and stare blankly at what comes out the other side. If we are to create that which has never been imagined before, we need only honestly and unabashedly listen.

### B. Sintering - Part I

Sintering is the process of heating a granular substance above its melting point so that its particles coalesce into one another. Given time, heated regions of a sintered substance cool and harden. The Moon presents two main ingredients that can be used as buildings materials: lunar regolith and solar energy. In alignment with the directive of only using what is available to us, lunar regolith can be robotically sintered using energy from the sun. Due to its elegant simplicity, the work required a way to use this process as a fabrication method to create structurally stable lunar architecture.

Framing how an extraterrestrial robot could execute sintering-based operations entirely in situ followed the same representational logic that previously proved fruitful. Measures of success and failure were determined by the ease with which a robot could build in different scenarios and ability for resulting forms to hold their shape. To do so, kinetic sand was used in lieu of lunar regolith. Kinetic sand is a granular material that retains its shape when sculpted, similar to clay or wet sand. Designed to be as close to actual extraterrestrial sintering as possible, it was exploring the design process that elicited moments of truth, not the actual construction method. This is to say, 3D printing and sintering methods were not physically executed via machine, but by hand. Doing so not only grants its user an intimate perspective of what is unfolding, seeing firsthand what works and what does not, but leaves space for what the actual construction method could be.

The method was explored in a very simple, playful fashion. My movements were like that of a potter sculpting clay, possessed with an unbound curiosity in the limitless possibilities this substance holds. Forging unconventional and abstract shapes to intentionally spur failure allowed its performance extents to be revealed. Lunar regolith's poor tensile properties quickly became

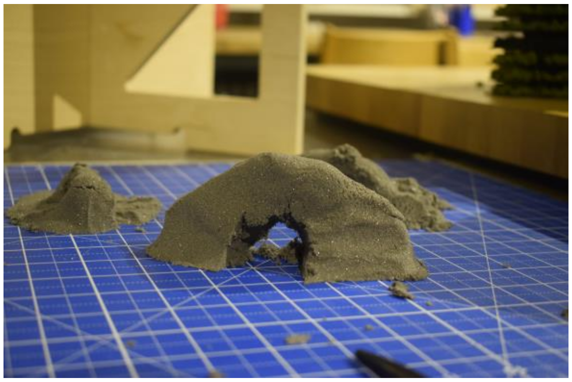


**Image 7. Compressive Form made solely In Situ.**

clear. Thus, I simulated the process of creating forms in compression with my hands in sequences a robot could execute enabling them to retain their shape.

Initial failures included the methodology's inability to build in different areas. Evidence of this came predominantly in the form of fractured kinetic sand. Virtually any surface without a strong foundation either failed or required an extremely light touch to hold together. Cantilevers or any sort of baseless plane surely collapsed. Even molding separate arcs and joining them together, as though prefabricated pieces, proved fruitless. A massive breakthrough came with Image 7. Such was the first form able to hold its shape in compression via a construction methodology solely using native building materials. The procedure required excavated material to first serve as falsework and removed only once the structure could support itself in compression. The idea of using lunar regolith not only as a building material but as support scaffolding set the groundwork for the most compelling discoveries of this research to be had. This helps illustrate one of the project's most unique aspects in that the construction methodology needed to become part of the architecture's journey for all criteria to be effectively met. (Like tying your shoe!)

**Image 8. "RegoLight" habitat showcasing its assembly via intricately designed building blocks.**

"RegoLight" is a prime example of a project activating land-driven principles to build in extraterrestrial settings. A unison of five partners, they are a pioneer alongside the ISS for what togetherness can do. Exploring the potential of fabricating lunar regolith "bricks" using the sun as an infinite energy source, their work is proof that creative methods to building with other planets, on their terms, do exist and are possible. Strategic assembly is charted using software that fits pieces together like a puzzle. Excitement abounds exploring the countless configurations offered by such an approach virtually. However, where this method and hand crafting vary is the understanding of assembly. A robot of extreme dexterity and precision is required to fit blocks perfectly and unceasingly into place. Doing so by hand makes this clear. One is also a lot less likely to fall into the trap of scattering the same design across a site for the sake of efficiency, which would only prove to our astronauts' detriment. By fusing the potential of compressive structures with fabricated components, the opportunities are truly endless for what we can create.

### C. Sintering - Part II

Key areas of focus with a sintering-based approach became the properties of lunar regolith and post-production form performance. With form generation contingent on the process by which it is built, the two must work as one and inform the other of where improvement is needed. This also included previously established criteria such as the form's ability to hold its shape, spatial efficiency, and The Prime Directive. Design versatility, or the ability to create more than just low-lying domes, also emerged as an important grading point.

Continuing with methods that simulate proposed processes of extraterrestrial building, I redirected the approach of previous sintering trials by introducing sugar and a blowtorch. As sugar has a lower melting point than kinetic sand, using it to simulate the process of coalescing granular particles into a solid fit the needs of the work exceptionally well. Thoroughly documenting these trials to maintain an iterative feedback loop, blowtorch heating limitations and test time constraints were acknowledged prior to experimentation to limit inaccuracy and preserve the project's integrity. These are examples of necessary compromises needed for discovery, like substituting kinetic sand for lunar regolith. Using analog methods to take the time to understand extraterrestrial building tools afforded this architect comprehensive insight as to the direction his work was heading in. Again, this underlines the importance of effective design process, a blatant stand against the profession's harrowing habit of only trusting computers to solve problems. The truth holds that you can go a million miles an hour, but if your direction is even the slightest bit askew, what good is it? Just because you can do something, does not necessarily mean that you should.

Progressing the cut and fill ideology, trials began by filling excavated sites with sugar to establish a layer of lunar regolith that could be sintered (via blowtorch). After heating the sugar, coalesced sugar particles would cool and harden into a solid. The resulting catenary was then flipped, securely held in compression, and able to serve as formwork. As these results proved unconvincing from a lack of curve pronunciation, the method shifted to applying the same technique to aboveground sites, starting here instead of an excavated basin. After compacting a mound to cast the catenary, sugar was spread over its surface and lit with a blowtorch. The resulting formwork, supporting itself in compression, only then required its former loose lunar regolith falsework to be removed from underneath it, no additional catenary flipping necessary.

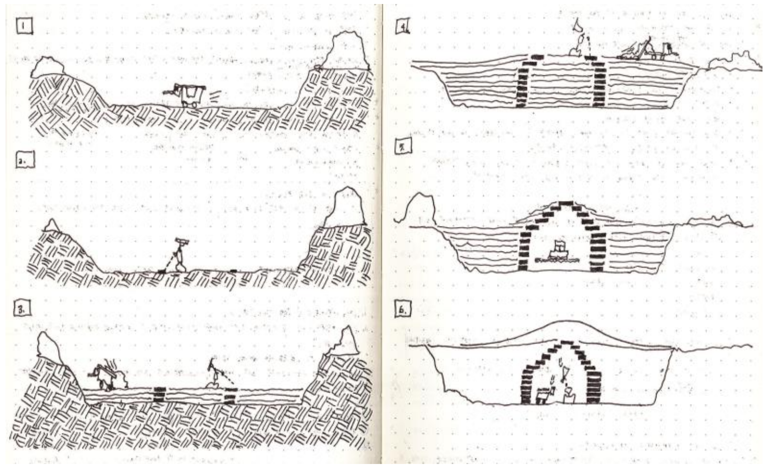


**Image 9. A simple, cut and fill approach that does more with less.**

Given the delicate balance between the sugar's melting point and energy expended from the blowtorch, one of two failures inherent to the experiment's design occurred: either too much heat was concentrated in a specific area, resulting in a bubbling and immediate liquification of the sugar; or not enough heat was transferred, producing only tiny surface bubbles. Such was the case with all initial cut catenary trials, the fruit of which became extremely low-lying domes with negligible curvatures. For aboveground sites, liquid sugar constantly flowed from top to bottom as heat from the blowtorch was applied. The model's summit, like fitting a keystone, proved the most difficult portion to sinter due to rapid state changes, unable to be fully sealed as a result.

One of the biggest issues with this approach is form versatility. Its inability to produce more than just an arch is a clear design flaw. Even with various refinements throughout testing, the process is still extremely limited in terms of the habitats it can make. With the help of my peers, however, an alternative approach surfaced. The idea applies the same use of lunar regolith falsework to hold sintered material in place except on a layer-by-layer basis. This way, once the form hardened and was able to support itself in compression, all the remaining falsework that enabled it to do so could be excavated. This not only fully leverages the land we engage as tried in previous attempts, but allows for virtually any compressive architecture to be built given its improved support system.

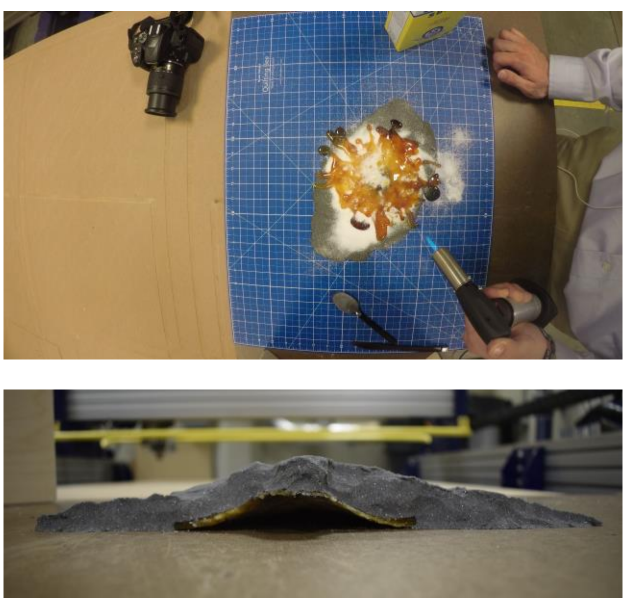


**Image 10. Design Process Evolution.**

Image 10 displays a giant leap forward for these studies as it addresses key criteria with compressive forces supporting the necessary thickness of lunar regolith for complete crew protection. Among other severe dangers, the need for such a bulky exterior is chiefly due to the Moon's lethal levels of solar radiation and micrometeorites that can reach speeds up to 100,000 km/hr. This was an incredible feat most notably because it remains in direct alignment with The Prime Directive, truly building with the Moon.

By deliberately acting out each step of a 3D printer and sintering device by hand, I came to understand how construction might unfold on another planet. I learned that it is not about throwing coordinates into a machine only to see what it spits out next. Destination-oriented mindsets such as this ravage society. Far from just with architecture, such can be found at every corner of life. People using people to get what they want, only to discard them when convenient. Careers spent doing monotonous, passionless work merely for monetary gain. Even some of my classmates at school: only doing what is required and going through the motions to obtain a degree. Where is the passion, the love, the life in that? This is by no means a judgement as everyone's circumstances are different. However, if we continue to take an attitude that only looks to the final outcome for fulfillment instead of getting to know every step there in an intimate way, we will never unlock our full potential. Design is also such a journey. Therefore, modeling kinetic sand by hand in a step-by-step fashion brought with it an abundance of insight that could have never been possible by letting the computer have all the fun.

Nowadays, architects are far too willing to jump right to digital tools without even considering their analog counterparts. The deliberate rejection of and unwillingness to listen to project needs to, instead, churn out buildings in a more time and cost-effective fashion is the very snare that is strangling our planet today. This is precisely what the cookie-cutter world of Revit architecture has created: soulless, one-dimensional spaces you can pick from a catalog. Architects that mindlessly implore such tactics do not listen to or care about what people or sites need, they are strictly concerned with what is most profitable. You need a detail? It is in a farm. There is zero thought and creativity put into these projects. Then, they are plopped on top of any old site where they suffocate the local community. Do this enough times, it becomes a global issue, and that is exactly where we are today. Again, short-term profit in exchange for long-term consequences. For crying out loud, Canon VI of the American Institute of Architects' "Code of Ethics" is dedicated entirely to our obligations to the environment. Is this really the best we can do? Furthermore, mindless design process fails to exercise the divine muscles we are blessed with that permit us to think outside of the box. We cannot allow the same thing to happen on the Moon. Rather, by taking the time to carefully consider each and every step of the construction process by hand, a fuller understanding and appreciation of outcomes is had. This not only allows for more responsible decisions to be made, but mistakes to come to light earlier in the process of making that otherwise reign supreme when a blind eye is turned to what the computer did.

**Image 11. Is this how architects are to use the power of design?**

## IV. Conclusion

This work was reviewed by a panel of experts with backgrounds including architecture, aerospace engineering, chemistry, and digital fabrication among other fields. Such a group reflected the very principle of building with one another that this project aims to be a shining example of. As a result, robust creativity spurred from diverse and interdisciplinary perspectives. Examining the material constraints of lunar regolith and the extents of its performance prompted ethical questions that sought to slaughter The Prime Directive. For instance, is a terrestrial-material modification acceptable if such ingenuity proved profitable? The tendency to sacrifice moral standing for passing pleasures such as profit, material gain, and convenience is something our species struggles mightily with. As a member of a space architecture community who does not fear failure, but embraces it, I strongly believe the rigid constraints that a space project presents are where design thinking not only has an opportunity, but an obligation to intersect. It is the practice of creative, outside-the-box exploration that makes this work as fulfilling as it is. We must use these powers for good. Thus, it profiteth no one who sacrifices their soul to gain the world.

Sometimes, especially as architects, pencil needs to meet paper. Taking the time to understand what it is you are doing and why before you go and do it is an all-important first step for any project. The innate connectivity between mind and hand, while intangible, is invaluable and illuminates discoveries that are essential and unique to every work. There will always remain the known unknown, and there will be times things simply do not go the way we thought they would. However, this only further emphasizes the importance of doing everything in our power to fulfill the ethical obligations of a project, especially with humanity's first extraterrestrial architecture. Design research culminated in a two-part conviction that must be allowed to inform the built environment of both terrestrial and extraterrestrial domains: 1. Set ethical intentions based on what we know that, in turn, drive criteria; 2. How we do it, the design process, must fully embody these from start to finish. Such are absolutely necessary first steps if we are to serve for the greater good of humanity, taking care of what is most important first so that everything else naturally flows into place. While such shifts to design process will not yield an overnight transformation, they do promise the slow and steady rebuilding of our civilization and hopeful eyes set on harmonious horizons. This work is proof that we can do it. The truth is, building with celestial bodies starts with a mind and hands.

We need to learn how to crawl before we can walk, to walk before run, and run before sprint. This not only holds true for completing one structure, but the entire extraterrestrial vision. In other words, a lunar master plan means nothing until you first do a habitat right. Furthermore, humans are already beginning to adopt in situ practices in terrestrial settings, activating the land in holistic ways. James Turrell is one such pioneer that, through notable works like Roden Crater and the Irish Sky Garden, taps vast reservoirs of appreciation and respect for the world. We are sitting atop mountains of untapped potential that is just waiting to be unleashed. These examples, among countless others, prove that extending the design process to include all sentient life is, in fact, something that humans are not only interested in, but innately crave to do. In many ways, a new light is cast on the age-old war that rages on between life and death: do we continue to line our pockets with design that destroys worlds? Or will we listen and do only that which is best for both our species and the planets we dwell? It is this author's firm belief that time and a patient determination are required in order for us to get it right.

We know from Earth that a building's life continues long after it is built. The process of how we build must reflect this idea of architecture being a journey, not a destination. This namely concerns our approach, and the Earth is screaming at us that our approach needs work. If we want to ensure the survival and growth of our species, remaining true to what we feel in our hearts and the ethical prime directives we set is paramount. We cannot pillage and exploit the resources of the Moon's surface the way we have on Earth. The Moon, like Earth, is special, and needs to be treated so. By proving that we fully understand this, which solely building in situ is a start, humans will avoid spreading the same self-destructive habits festering on Earth across the Universe.

## Acknowledgments

This work could never have been made possible without the support of Wentworth Institute of Technology, Robert Cowherd, Brent Sherwood, and Dahlia Roberts.

## References

[1]Aimee Delach, "Harnessing Nature: The Ecosystem Approach to Climate-Change Preparedness," Defenders of Wildlife, 2012.

[2]Aaron Betsky, Landscrapers: Building with the Land (New York, NY: Thames & Hudson, 2006).

[3]Betsky, Landscrapers.

[4]Ibid.

[5]Aimee Delach, "Harnessing Nature: The Ecosystem Approach to Climate-Change Preparedness," Defenders of Wildlife, 2012.

[6]Sarah Soliz, Laura Symonds, and Christine Willan, "Reduction, Reuse, and Recycling on a Future Lunar Base," in Engineering, Construction, and Operations in Space IV, ed. Rodney G. Galloway and Stanley Lokai (New York, NY: American Society of Civil Engineers, 1994).

[7]Aaron Betsky, Landscrapers: Building with the Land (New York, NY: Thames & Hudson, 2006).

[8]Chris Impey, Beyond: Our Future in Space (New York, NY: Norton, 2015).

[9]Aaron Betsky, Landscrapers: Building with the Land (New York, NY: Thames & Hudson, 2006).

[10]Betsky, Landscrapers.

[11]Brent Sherwood, "Comparing Future Options for Human Space Flight," Acta Astronautica 69 (2011): 346-353, https://doi.org/10.1016/j.actaastro.2011.04.006.

[12]Brent Sherwood, "What's the Big Idea? Seeking to Top Apollo."

[13]Brent Sherwood, "Comparing Future Options for Human Space Flight," Acta Astronautica 69 (2011): 346-353, https://doi.org/10.1016/j.actaastro.2011.04.006.

[14]Neil Leach, "3D Printing in Space," Architectural Design 84, no. 6 (2014).

[15]Sarah Soliz, Laura Symonds, and Christine Willan, "Reduction, Reuse, and Recycling on a Future Lunar Base," in Engineering, Construction, and Operations in Space IV, ed. Rodney G. Galloway and Stanley Lokai (New York, NY: American Society of Civil Engineers, 1994).

[16]Soliz, "Reduction, Reuse, and Recycling."

[17]Brent Sherwood, "Technology Investment Agendas to Expand Human Space Futures," (Reston, VA: American Institute of Aeronautics and Astronautics, 2012).

[18]Brent Sherwood, "Principles for a Practical Moon Base," (Paris, France: International Astronautical Federation, 2018).

[19]Sherwood, “Moon Base.”
[20]Ibid.
[21]Ibid.
[22]Ibid.
[23]Ibid.
[24]Ibid.
[25]Paul J.A. Lever, Fei-Yue Wang, and Deqian Chen, “Intelligent Excavator Control for a Lunar Mining System,” in Robotics for Challenging Environments, ed. Laura A. Demsetz and Paul R. Klarer (New York, NY: American Society of Civil Engineers, 1994).
[26]Brent Sherwood, “Principles for a Practical Moon Base,” (Paris, France: International Astronautical Federation, 2018).
[27]Paul J.A. Lever, Fei-Yue Wang, and Deqian Chen, “Intelligent Excavator Control for a Lunar Mining System,” in Robotics for Challenging Environments, ed. Laura A. Demsetz and Paul R. Klarer (New York, NY: American Society of Civil Engineers, 1994).
[28]Brent Sherwood, “Principles for a Practical Moon Base,” (Paris, France: International Astronautical Federation, 2018).
[29]Oscar Firschein, Artificial Intelligence for Space Station Automation: Crew Safety, Productivity, Autonomy, Augmented Capability (Park Ridge, NJ: Noyes Publications, 1986).
[30]David Torres, “Construction of a Lunar Base,” in Engineering, Construction, and Operations in Space IV, ed. Rodney G. Galloway and Stanley Lokai (New York, NY: American Society of Civil Engineers, 1994).
[31]Neil Leach, “3D Printing in Space,” Architectural Design 84, no. 6 (2014).
[32]Brent Sherwood, “Principles for a Practical Moon Base,” (Paris, France: International Astronautical Federation, 2018).
[33]David Torres, “Construction of a Lunar Base,” in Engineering, Construction, and Operations in Space IV, ed. Rodney G. Galloway and Stanley Lokai (New York, NY: American Society of Civil Engineers, 1994).
[34]Torres, “Construction.”
[35]Ibid.
[36]Neil Leach, “3D Printing in Space,” Architectural Design 84, no. 6 (2014).
[37]Leach, “3D Printing.”
[38]Brent Sherwood, “Principles for a Practical Moon Base,” (Paris, France: International Astronautical Federation, 2018).
[39]Sarah Soliz, Laura Symonds, and Christine Willan, “Reduction, Reuse, and Recycling on a Future Lunar Base,” in Engineering, Construction, and Operations in Space IV, ed. Rodney G. Galloway and Stanley Lokai (New York, NY: American Society of Civil Engineers, 1994).
[40]Brent Sherwood, “Space Architecture for MoonVillage,” Acta Astronautica 139 (2017): 396-406, https://doi.org/10.1016/j.actaastro.2017.07.019.
[41]Neil Leach, “3D Printing in Space,” Architectural Design 84, no. 6 (2014).
[42]David Crenshaw, Patrick Cigno, Phillip Kurtis, Gerry Wynick, Wang Xingwu, Ryan Jeffrey, Carol Craig, Sam Deriso, and Jim Royston, “To Infinity and Beyond: Outer Space Applications of 3D Ceramics Printed via Inkjet Methods,” American Ceramic Society Bulletin 97, no. 6 (2018).
[43]Neil Leach, “3D Printing in Space,” Architectural Design 84, no. 6 (2014).
[44]Leach, “3D Printing.”

## List of Figures

Image 1 - Pergamon Acropolis (©David John). “Pergamon, Turkey, 2004,” My Favourite Planet, accessed 2 December 2018, http://www.my-favourite-planet.de/images/middle-east/turkey/pergamon/pergamon_dj-14042004-0276_acropolis-hellenistic-theatre.jpg.

Image 2 - Göreme in the Cappadocia Region of Turkey (©Street Credd). “Göreme, Turkey, 2018,” accessed 8 March 2020, https://streetcredd.com/wp-content/uploads/2018/08/Goreme-in-the-Cappadocia-region-of-Turkey-1024x682.jpg.

Graph 1 - NASA Budget as a Percentage of Federal Budget (©Wikimedia Commons). “2014,” NASA, accessed 2 December 2018, https://upload.wikimedia.org/wikipedia/commons/0/09/NASA-Budget-Federal.svg.

Image 3 - Roden Crater (©The Center for Land Use Interpretation). “Arizona, 2013,” The Center for Land Use Interpretation, accessed 9 July 2020, https://www.clui.org/sites/default/files/imagecache/clui-image/clui/post_images/2012-05-22-09-59-55.jpg.

Image 4 - Irish Sky Garden (©Liss Ard Estates). “Skibbereen, Ireland, 2020,” Atlas Obscura, accessed 9 July 2020, https://assets.atlasobscura.com/media/W1siZiIsInVwbG9hZHMvcGxhY2VfaW1hZ2VzLzk3ZGMyNzJlZTk5ZDQ3OTNlNF9HYXJkZW4uanBnIl0sWyJwIiwidGh1bWIiLCJ4MzkwPiJdLFsicCIsImNvbnZlcnQiLCItcXVhbGl0eSA4MSAtYXV0by1vcmllbnQiXV0/Garden.jpg.

Image 6 - Foster + Partners, “Lunar Habitation,” YouTube Video, 4:54, 19 July 2018, https://youtu.be/MUKYJWFpiD4.

Image 8 - Liquifer Systems Group, “Regolight Sintering Regolith with Solar Light,” YouTube. 11:19, 26 April 2018, https://youtu.be/jVCiPTXYYu8.

Image 11 - Google Maps. “Revit Strikes Again in Queens, NY,” accessed 9 July 2020, https://www.google.com/maps/place/Queens,+NY/@40.7612016,-73.9293216,538a,35y,270h,39.33t/data=!3m1!1e3!4m5!3m4!1s0x89c24369470a592b:0x4109d18b6c5c7b05!8m2!3d40.7282239!4d-73.7948516.