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MPIT: Minimally Processed ISRU Technology Structures for Rapid Extraterrestrial Settlement Infrastructure Development

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To execute successful extraterrestrial missions farther out in space, it is prudent to test, evolve and master useful technologies in extraterrestrial environments that are close to Earth. A high-fidelity simulated settlement on our Moon would be the perfect proximal extraterrestrial location to test and certify new technologies for more ambitious missions planned for destinations much farther away. A lunar settlement could be used to prove that creating sustainable settlements at farther locations, such as Mars, would be successful in the long run. It is vital to learn to reliably quarry, manipulate, transport and accurately emplace large masses in specific locations for construction of settlement infrastructure. This technique is feasible especially in low gravity environments like our Moon and Mars. Use of such tools and equipment to create and reliably replicate a system of permanent and reliable roads, landing areas and dust free zones can accelerate extraterrestrial infrastructure buildup. Lunar dust can prove hazardous to a mission because it has proven to degrade past mission performance and mission equipment. Dust mitigation is a critical issue. Minimal technology would be available during the initial stages, yet sturdy, long lasting and reliable structures that form the backbone of the infrastructure are critical to any permanent extraterrestrial settlement infrastructure establishment. Minimally Processed ISRU Technology (MPIT) proposed in this paper is an economically viable, tried and tested method for development on Earth. MPIT should be adopted as the core strategy employed for any extraterrestrial settlement development using lessons from established and reliable heavy machinery adapted for the extraterrestrial environment with state of the art robotics, automation and communication technologies for extraterrestrial use including such activity on our Moon and Mars.

Nomenclature

ISRU	=	*in situ* resource utilization
MPIT	=	minimally processed ISRU technology

I. Introduction

A major near term goal in the area of space exploration has been to successfully execute extraterrestrial missions with the aim to build up permanent infrastructure. An important stepping stone to be able to achieve this goal is the testing of technologies and evolving suitable mission plans. Simulations on the Moon can provide scientists and engineers with the ability to test and certify these technologies while still being within close proximity of Earth. This provides a safer platform to do any necessary tests and evolving reliable systems for certification, while also allowing rapid iteration to achieve a high level of confidence. The major limitation of creating a physical infrastructure on the Moon to conduct mission simulations is the paucity of initial landed surface systems and technology that would be available to astronaut crew. Therefore, there must be an initial phase of development focused on using very reliable, low-energy, high output methods to produce resilient groundwork, which can then be used to bootstrap the creation of more complex and reliably-functioning lunar infrastructure.

It is well established in the practice of civil engineering that much of the physical infrastructure in the development of settlements lie not in building and commissioning habitats but in laying out the supporting infrastructure that has to reliably weather and withstand the rigors of physical development activity. This includes the construction of roads and platforms, foundations, walls and other supporting elements. For building extraterrestrial structures, support

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infrastructure and machinery alike have to deal with issues like vacuum, low gravity, thermal, micro-meteoritic and radiation environment as well. The initial groundwork would be a system of permanent and reliable roads, landing pads and associated areas, and dust-free zones. The schematic layout of a lunar settlement with a landing pad in Figure 1. shows the extent of groundwork that is needed to support a serviceable settlement.

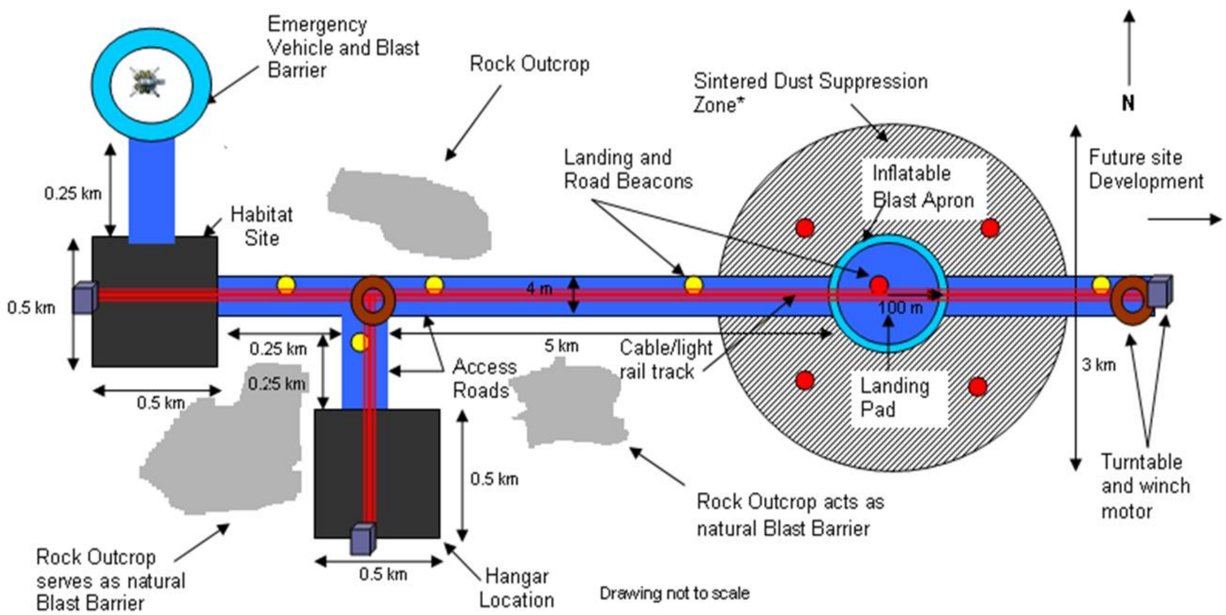

Figure 1. Schematic layout of a lunar settlement with a landing pad show the extent of groundwork that is needed to create a serviceable permanent settlement. The habitation zone is small compared to the rest of the infrastructure. Distances are not to scale.(Thangavelu 2009)

Creating roads and landing areas are a critical part of transportation and mobility, while creating dust-free zones is also important because dust has historically proven to degrade mission performance due to its interference with mission hardware. (Gaier 2005)

II. Methodology

The proposed solution to create rapid infrastructure on the Moon with minimal energy is to revert back to basic archaic structures and technology that can be created using *in situ* resources and simple tools (Thangavelu 2000). These structures would be efficient and long lasting. The ultimate goal is to use minimal energy methods such as quarrying, breaking, crushing, shaping, grinding, and precise positioning of elements like blocks and tiles. This allows astronauts to construct long-lasting structures without relying on advanced methods for initial colonization missions.

There are several historical examples where this use of minimally processed technology was successfully used to construct strong and long lasting structures in the past (Abrams 1994). One very good example is the network of durable roads built by the Ancient Romans.(Lawrence 2002) The Romans built their roads with several aggregate layers of stone and rock, show in Figure 2. The lowest layer of the road consisted of larger sized stones to create a base, and the layers that followed consisted of stones in decreasing size. The second layer was made from pebbles and sand, created from crushing stones. This layer was followed by a coat of cement topped with a final layer of paving stones, which were finely cut and packed together tightly. The technology that was used to create these roads was limited to simple contraptions. Ploughs and spades dug the majority of the trenches. The inclinometer was an extremely crude level used by the Romans for ensuring flat roads. It was composed of a plumb line suspended from the triangle, with a mark indicating horizontal. As an example, this simple device would function just as well on the Moon. Although the Romans did rely on human labor for most of the rock-laying, they made use of rollers to compact the layers together (Shuttleworth). Replicating this methodology can enable us to create efficient and long lasting structures using low energy MPIT methods.

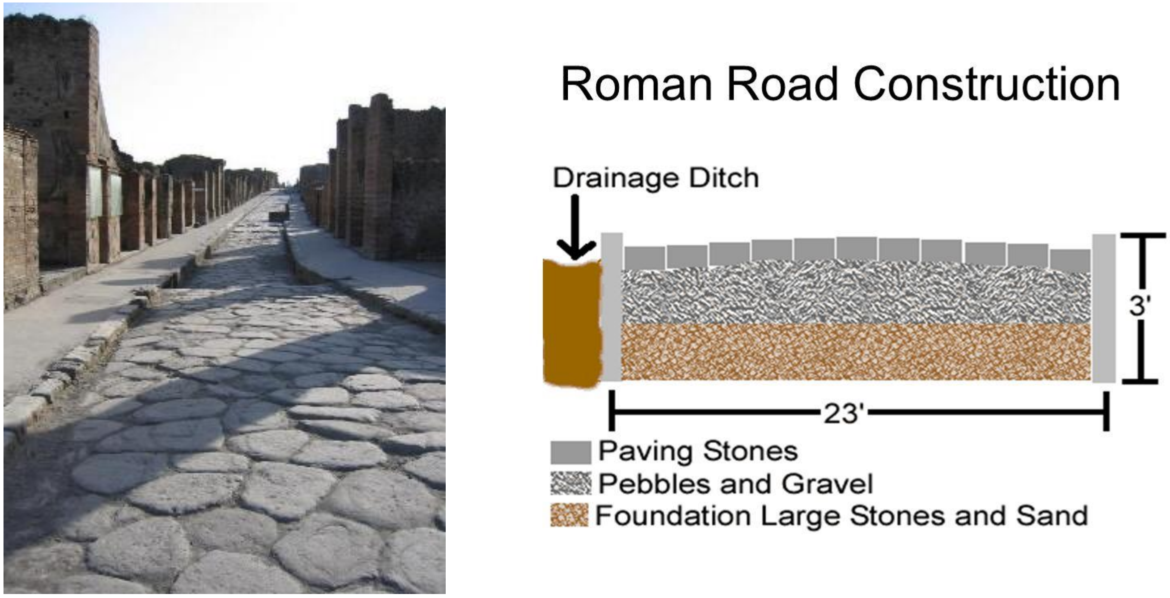

Figure 2a,b – 2a shows Roman roads are known for their strength and durability ("Modern"). 2b shows typical section of various grades of aggregates used for resilience and durability (Norris).

A. The Proposed Method

The proposed MPIT method to perform rapid, low energy infrastructure development on the moon is to use well-established Earth construction machines modified to work in an airless lunar environment. The adapted technology should then be able to utilize *in situ* resources quarried from lunar basalt to produce building materials for necessary structures for an initial settlement. By utilizing updated technology while still maintaining the construction philosophy of ancient structures, the produced lunar infrastructure will be able to be feasibly produced within limitation and also be long lasting.

1. Material Selection

The first step would be to locate and isolate the *in situ* resources necessary for the development. Igneous rock is commonly used for construction of structures and roads on Earth. Basalt, a type of igneous rock, is generally present in high concentrations in the Mare regions on the Moon. Figure 3 shows lunar rocks which could be excavated and used to produce construction aggregates for the purpose of creating infrastructure. The Highlands are often littered with large boulders, making navigation and excavation difficult and dangerous. Therefore, it is proposed that the Mare regions of the moon be utilized for obtaining the necessary basalt to create structures necessary for an initial development. Methods to quarry in such locations need further study and development.

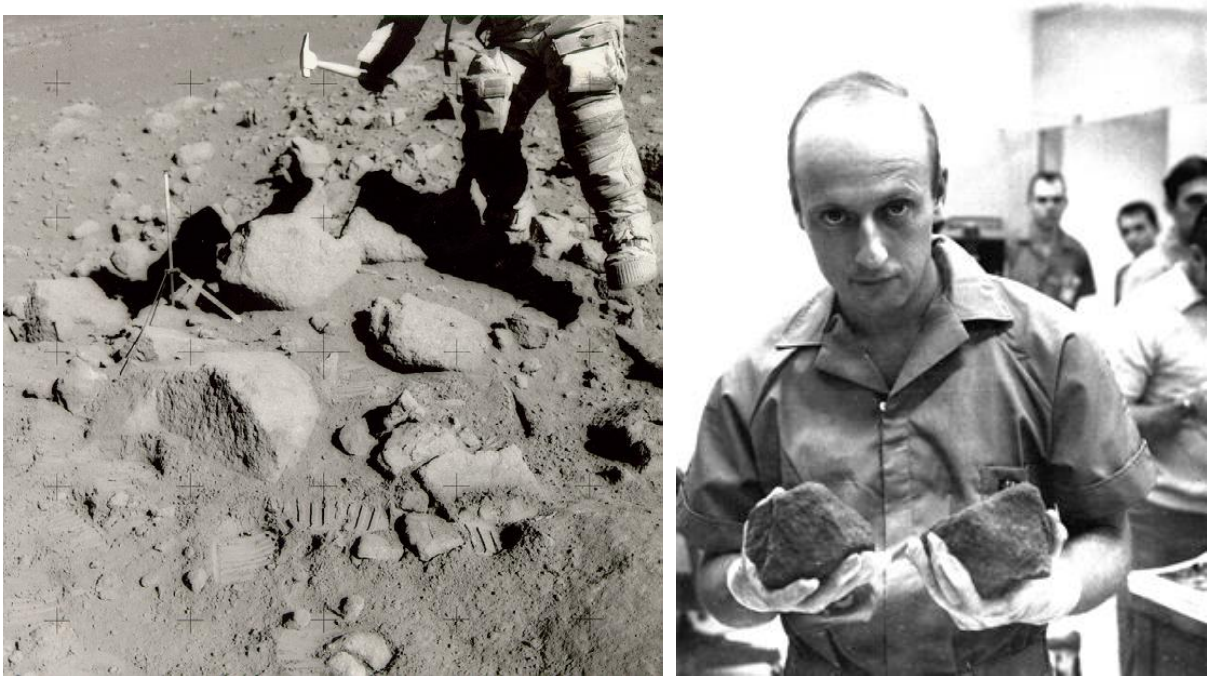

Figure 3a,b – Apollo 15 photograph showing an astronaut breaking small chips off rocks ("Project").3b show lunar rocks brought back to Earth that can be gathered on site, shaped and used for building a variety of infrastructure ("Apollo").

2. Crushing Aggregate Material

The next component to consider is the technology that should be utilized to convert the lunar rocks into structures. There are several established technologies that can do this on Earth, including rock cleavers, cutters, shapers, crushers, sorters, and sieves. Of these, the cone crusher, shown in Figure 4 and Figure 5, is particularly capable of being adapted to function effectively in a low gravity environment. The cone crusher is able to accept many different sizes of quarried materials, and can naturally sort them while it rotates. The cone at the center of the machine rotates to produce crushed aggregate of varying sizes, depending on its angle of rotation. The quarried material in the crushing chamber are then crushed to the desired size. The cone crusher has a number of advantages. Cone crushers are currently able to be operated with electric motors, which do not require oxygen to function ("Crushing"). This means that they would be able to function in space. Additionally, it can be easily adjusted; changing the reduction ratio is mostly a matter of adjusting either the height or the eccentricity of the cone. This provides the operator with the flexibility to create variable-sized aggregate using a single machine. One disadvantage of the cone crusher is the low reduction ratio compared to other crushers, such as the impact crusher. The cone crusher typically achieves a maximum 8:1 reduction ratio, while impact crushers can go as high as 24:1. On the other hand, the impact crusher will abrade quickly when crushing basalt, and it operates at high power with a large actuator arm, which makes it less reliable. It is also important to consider that the surface of the Moon is mostly dust, which can be trivially collected as a substitute for the smaller aggregate that would have been generated by impact crushers.

A challenge with using a cone crusher is that high energy debris would be generated from the crushing process, and therefore have to be curtailed at the source. An important modification that would have to be made to the machine is that the machine would need to trap high energy debris. In addition, by capturing high energy debris and sorting the particles by size, larger sized particles could be identified and set aside for structures they would be appropriate for. After the modified cone crusher traps the discharged material, the material would then be sifted to sort the material by size. This is important because the size of the aggregate required to compose a structure will vary. This process is meant to be completed with minimal human interaction, so by sorting the crushed lunar rocks, the astronauts will have an easier time transporting necessary materials to their assigned locations. Once the materials are sorted, the finer materials will be used to produce layers for roads or bricks while the larger materials will be transported by rovers.

Figure 4a, b – 4a shows a cone crusher crushing rocks into finer materials ("P&Q"). 4b shows a slab cutter at work in the quarry ("Quarry"). Large slabs cut from lunar basalt could be used to pave landing pads and roads, and to build dustfree platforms on which habitats and other structures may be erected.

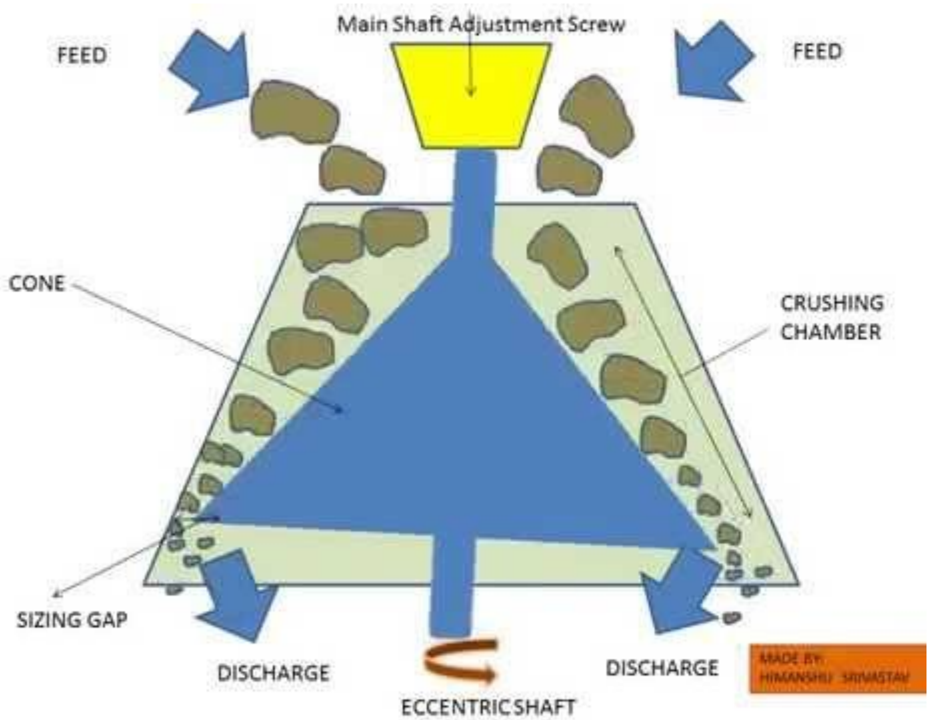

Figure 5 - Diagram of a cone crusher (Srivastav).

3. Effects of a Lunar Environment

However simple they are, traditional cone crushers will require some modification to operate successfully in lunar gravity. In general, the operating efficiency of the crusher is significantly reduced on the Moon since it relies on friction against the cone to break rocks into chunks. Friction is proportional to the normal force, which will be 1/6th of its Earth magnitude. As a result, there will be much more bouncing around of the lunar material inside the crusher, which means that the crusher would, at a minimum, have to be modified to contain a roof. The bouncing may provide indirect benefits, however. Conventional cone crushers have an expensive wear liner made of manganese that coats the cone and bowl, which nominally wears during use. Reduced friction and increased bouncing will likely cause rocks to wear against each other to a higher degree than they do on Earth, decreasing maintenance on the crusher at the expense of slower crushing. This is significant given that basalt is about the same level of hardness as manganese. It is also important to note that the manganese steel wear liner can be replaced in situ due to the substantial presence of manganese on the Moon.

4. Construction Process

The machined rock and variably-sized aggregates would be used to form layers and ultimately bricks that were meant to fit together and create structures necessary for initial lunar settlements. The debris trapping system built into the machine would be used to create the finer construction aggregates and lay the foundations of the roads. It is important that finer construction aggregates are able to be utilized because the surface of the roads should be kept relatively smooth to allow rovers to be able to easily traverse the area to carry construction materials. If roads are not smooth, rovers carrying heavier payloads may have trouble traversing the paths. Slabs cut from quarried lunar basalt may therefore be quickly transported and emplaced over terrain that has been stabilized and prepared with various layers of aggregate. The constructed roads and platforms would then be able to be used for rovers to transport other large masses for further construction and habitat module assembly.

The construction method referred to as “dry packing” has been particularly effective in ancient structures (Thangavelu, 2012). The structures created with this method with the construction aggregates produced from the cone crusher are expected to be sturdy and long lasting. Using dry packing, construction materials could be formed and utilized efficiently, while also allowing for the possibility of reusing the larger aggregates. An example of this can be observed in Newgrange, a 5,200 year old passage tomb that was constructed with similar methods, shown in Figure 6. Similarly to Newgrange, the bricks produced from the cone crusher’s aggregate curtailing process would be able to be utilized to create surfaces resembling the depicted tomb wall.

The potential structures that could be developed from this construction method include landing pads, roads, platforms, shade walls, towers, landmarks and markers, pilot VFR aids, and perimeter demarcations. Some of these, such as perimeter demarcations require less precise fitting of stones together, would be an optimal fit for the larger-sized aggregates that would be produced from the crushing and dry packing process. Along with natural regolith, finer aggregates that are produced from the process could be packed and filled into bags or layered into stone to build more intricate structures such as roads, walls, or towers.

Figure 6a,b – Stonehenge, in 6a, is an example of a rock structure that was quarried and erected 2500 years ago (“History”). Dry packing technology at the 5200 year old Newgrange Tomb Wall, shown in 6b, show the capacity of handbuilt rock structures to weather the elements (Stout).

Figure 7a,b The Egyptian pyramids and Sphinx, shown in 7a (Bart), were built 4500 years ago, and the Greek Parthenon, shown in 7b ("The Parthenon"), from 2500 ago are rock structures that were built with hand tools and still possess structural integrity. The pyramids also have great insulation properties attributable to thermal intertia, holding steady internal temperatures during the extreme diurnal thermal cycles of the desert. This property could be an asset for extraterrestrial rock structures.

B. Alternate Methods

There have been other solutions described in literature to create structures for initial settlements on the moon. Making concrete from regolith has been tested (Lin 1982, 1987) and using sulfur to produce concrete from regolith has been studied (Omar 1994, Khoshnevis 2012).

1. Sintering

A lot of consideration has been paid to sintering technology to create roads on the lunar surface. Sintering is the process of coalescing powder into a solid or porous mass by applying heat resulting in superficial melting of the material (Taylor 2005). The surface of the material is melted to adhere to form a solid mass using microwaves. Sintering would allow regolith stabilization quickly and efficiently, however the method has some limitations. Surfaces created by sintering are characteristically brittle, which means that they would also be susceptible to fracture. This may not be ideal for lunar roads because heavy materials for building settlements would have to be transported on the roads, and a brittle road would likely be unable to handle the stress. In addition, if there is a fracture on the road due to excessive point loads caused by events including accidents, it could be difficult to repair with large machinery without creating subsequent fractures of the material. The fractures would be difficult to repair without removing and replacing large portions of the road due to the relative difficulty of sintering on existing objects.

Lastly, surfaces created from sintering would be susceptible to fracture under lunar thermal cycling and selective sintering has been proposed as a concept to circumvent this problem (Khoshnevis 2014). The sintering process also requires precise control over the temperature of the material on the order of 25 degrees (Rosidah). Because of a lack of atmosphere, lunar surface temperatures can fluctuate between 100 degrees K to 387 K (Malla). It would be difficult to properly sinter material in the lunar environment due to these fluctuations. Therefore, while sintering could be an effective option to create roads and structures efficiently, the resulting structures would need advanced technologies and perhaps not as resilient or ideal for this application.

2. Additive Manufacturing

Another potential solution to create fast and long-lasting structures for initial lunar settlements is to use additive manufacturing to create the previously mentioned structures (Khoshnevis 2012). By utilizing additive manufacturing, a variety of structures could be produced without requiring custom tooling. The single tool could produce any designed structure, and the structures could be optimized for specific applications. The limitation to using additive manufacturing are that there are high maintenance and supervision costs. In addition, the manufacturing process is both time- and energy-intensive, and utilizes complex equipment. These factors combined result in a higher-energy technology-intensive manufacturing process that would not be ideal for an initial settlement posed with minimal available resources.

III. Discussion

Low energy, high impact and rapid methods are sought for building up extraterrestrial infrastructure, especially during initial phases of buildup when there is a paucity of surface systems and construction machinery. It is established that much of the energy and resources expended in permanent habitation establishment lie not in erecting and deploying habitats but in creating underlying physical infrastructure like roads, shoring and shade walls, radiation and micrometeorite protection and laying down dust-free platforms and utilities. Note that large rocks offer excellent thermal inertia, and like the pyramids(see figure 7a) and other huge structures can offer a steady thermal environment, especially during the large diurnal swings in temperature seen on the Moon and Mars.

The proposed method to use minimally processed ISRU technology (MPIT) for rapid settlement infrastructure development is advantageous for several reasons. Roads developed by MPIT would be long lasting and resilient against severe diurnal temperature cycling. The surface of the Moon can expect approximately a 300 degree temperature differential in a 28-day cycle. This is one of the reasons that monolithic manufacturing methods such as sintering would not be ideal. Having a more robust, and less brittle and resilient road infrastructure will allow rovers to transport heavier construction materials to develop settlements more rapidly, such as large modular blocks and large area tiles.

A limitation of using larger scale robust manufacturing methods is that the dust and debris generated during production would have to be curtailed. Dust has historically proven to be a hazard to mission success because of interference with performance and mission equipment. It is critical to maintain dust-free zones, and this would have to be a major consideration for the proposed infrastructure development method. However, the proposed method would allow for the creation of designated dust-free zones as well. Therefore, if the dust were curtailed during the manufacturing process by adapting machines to confine the dust to certain areas, the ultimate benefit would be ideal for an initial settlement. Another setback associated with the proposed method is that structures may not be manufactured to the accuracy that would result from additive manufacturing. But for the applications including foundations, shade walls and barriers this issue may not be critical. It is important to consider that the goal for an initial settlement would be to produce high fidelity infrastructure with low levels of available technology. Adapting existing rock quarrying and construction technology using ancient methods to create long lasting structures is the goal proposed by MPIT.

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https://sites.google.com/a/usc.edu/aste527/home Look under SeleneOption 2016 section 04 MPIT ISRU

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