Pad for Humanity: Lunar Spaceports as Critical Shared Infrastructure

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Abstract

This paper focuses on the global-scale dispersal of dust expected to result from the increasing cadence and size of lunar missions and explores landing pads and/or "spaceports" as a means of mitigating these effects. Past studies have demonstrated the effects of dust, explored and modeled the characteristics of the regolith, and experimented with construction techniques. We review these findings and apply them to an analysis of the architectural design, operational considerations, and policy implications of what could be an early and important civil infrastructure of the Moon.

Definitions

Exhaust plume: high-velocity gas emitted from the nozzle of a rocket engine.

Ejecta: materials carried away by the exhaust plume. In the case of a lunar landing, this includes dust, sand, gravel, cobbles, and ablated material.

Spaceport: a facility providing a site for vertical rocket transportation to and from the lunar surface and supporting services such as refueling, recharging and maintenance.

Landing pad: The structure where a descending/ascending vehicle touches down.

Introduction

Mission data from Surveyor, Apollo and Chang'e 4 combined with terrestrial experiments and computer modelling all show that unmitigated surface landing and subsequent launches will significantly impact the lunar environment. This raises questions for future operations of surface and orbital assets, and coordination even amongst seemingly disparate lunar activities.

As the lunar community looks to move beyond infrequent, short-duration, and self-contained science missions, the potentials for damage or mission failure caused by high-velocity ejecta, geopolitical confrontations over these effects, and environmental compromise, suggest that lunar spaceports will be key to early infrastructure development. In-situ resource utilization (ISRU), utility services such as navigation, communications, and power, and other large-scale infrastructure in support of sustained activity, will all necessitate increasingly proximate operations in both space and time. The emergence of commercial activity on the lunar surface will only amplify the need to think about reliable lunar access and departure, and coordination mechanisms between autonomous actors.

Motivation: circumstances requiring regular landing & launch

In a sense, a spaceport is a kind of armor for the lunar surface since it protects the ground from the highly destructive force of the exhaust plume. Practically speaking this prevents the ground from becoming a spray of high-velocity projectiles that would necessitate armor for surrounding assets. In the absence of this surface armor all individual surface systems around the touchdown site will need to be armored, and thus more massive, undermining a mass-efficient mission architecture and globally adding engineering margins. While all surface assets will need to be engineered against the likelihood of micrometeorite impact and other incidental damage, the risk of ejecta damage will result in unnecessarily large engineering margins that levy substantial penalties felt at the level of the system architecture. For this reason, investing in the spaceport early is critical for both asset safety and programmatic durability.

Proximity operations. A functional lunar ecosystem will require some baseline physical proximity of operations to support the provision of infrastructure and services. Ground-based travel is expensive and therefore any moves towards proximity operations are likely to involve proximity landings as well. This is arguably even more likely for smaller class missions which may be more dependent on one another for mutual support. Economic development through the ability to buy and sell services, as well as investor confidence regarding mitigation of environmental threats to assets, will be aided by introducing certainty and reliability into the operating environment.

Commercial mining. Sustainable lunar activity is contingent on commercial mining. After commercially exploitable reserves are identified, mining, in contrast to mere prospecting, will involve decades of patience and billions of dollars in investment. All mining operations and their final products will require equipment for excavation, extraction, purification, synthesis, storage and distribution. The burden on spaceports as ports of entry for these payloads is evident. Moreover, these activities will inevitably require physical human intervention, necessitating crewed missions.

Building settlements from Earth. Earth to lunar surface flights, especially with the aim of establishing sustained robotic and/or human presence, will initially be the most consequential form of lunar launch and landing activity. Lunar actors will be world-building and so vehicles will be carrying at full capacity. Larger landing vehicles will be favored for their lower costs, wider margins of error and their larger payloads which will accelerate the agglomeration of base elements and supplies. Frequent landing and launch of heavy vehicles will be the norm.

Shuttling between settlements. Different regions of the Moon feature different concentrations of desirable resources - e.g. concentrations of water ice (a source of water, oxygen and hydrogen) in polar cold traps and concentrations of ilmenite (a source of titanium, oxygen and iron) in the lunar Mare. Lunar actors, especially those interested in ISRU, will be motivated to exploit complementary resources (e.g. water and metals) to gain their foothold on the Moon. “Hopping” flights between these sites may be the fastest and most reliable means of connecting them for trade. These vehicles will not be small since they will be transporting bulk goods and crew.

Tourism. Lunar surface tourism may revolve around visiting dramatic geological features or historic landing sights. Entities may also decide to visit heritage sites for public relations purposes; indeed, this has been announced already. (BBC News citation, 2016). The economies of scale required to make this financially feasible and the additional mass required to support human life support systems indicate that tourism activities are likely to involve larger classes of spacecraft.

Activity not requiring a Spaceport

In some instances, investment into construction and maintenance of a spaceport is unlikely to occur. These cases suffer from a short mission life, a lack of commercial viability, operational isolation, and/or a lack of interest in continual site development.

Science experiments. Scientists may wish to visit experiments after decades of data collection or exposure to the lunar environment. The short life of these missions and the possibility of conducting them with small (light) robotic vehicles that pose no tangible global ejecta threat makes them an unlikely case for spaceports or pads.

Resource prospecting. Space agencies and resource mining companies will aim to create accurate geological and exploitable resources maps followed by ground-truth prospecting. Prospecting is essentially a small-scale form of mining. The purpose of prospecting will be to decide where to establish long-term (commercially viable) mining operations which will themselves require a landing/launch solution. Prior to the identification of commercially exploitable resources, however, there may be few incentives to invest in a proper spaceport. This may not be true in every case and may depend on the nature of the identified reserves. Prospecting and mining sites may be near enough to existing settlements to warrant ejecta mitigation, and large or competitive enough to require repeated visits, heavier equipment (and therefore heavier landers), or concentrated activity in time (thereby requiring coordination). The motivation to invest in a spaceport, as in all cases, will depend on a specific tolerance for dust agreed upon by lunar actors.

Mechanisms

A lunar lander requires high-velocity rocket exhaust to produce thrust that counters lunar gravity during landing, but a flow of gas capable of supporting a several-ton vehicle is more than capable of also blowing rocks, gravel, sand and dust at high velocity. This creates a hazard both to the lander, to surrounding hardware on the Moon and to vehicles in space in the vicinity of the Moon. Experiments have shown that gas can interact with regolith in several different “regimes”, including viscous erosion, diffused gas eruption, shock impingement splashes, and bulk shearing of soil due to the high pressure directly under a nozzle (Metzger et al., 2009a; 2009b; 2009c). It is still unknown whether the much larger landers planned for the future will be capable of creating deep craters, but when their engine nozzles are very close to the surface it seems likely that the phenomena they induce will be different than and more violent than the Apollo LM (lunar module) landings. Experimental work is beginning to investigate these questions.

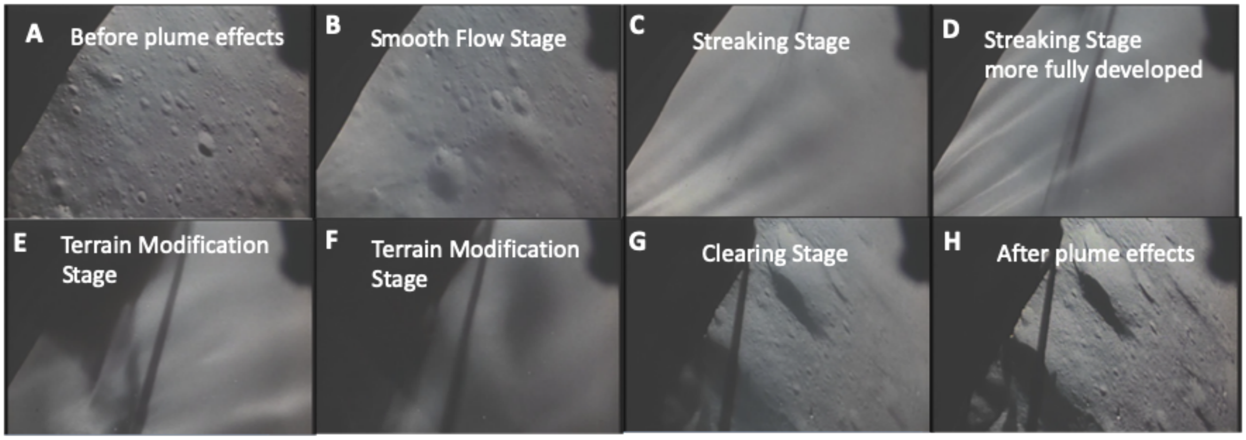


Figure 1: Stages of rocket exhaust ejecta beneath an Apollo Lunar Module (Metzger et al., 2011). In smooth and streaking flow stages, ejecta is mainly in a sheet 1-3 degrees above horizontal, although some individual streaks are at higher angles. In terrain modification stage much of the ejecta is lofted into higher angles exceeding 15 degrees.

If no crater forms, the boundary layer of the rocket exhaust lifts soil particles and carries them away in a largely radial direction. Analysis of the shadows of the landing Apollo LM seen in the descent videos (Figure 1) shows that the ejecta was mostly traveling in a sheet 1-3 degrees elevation angle above the local horizontal (Immer et al., 2011a), although ejecta can be seen flying at higher angles out of craters and a blast with higher ejecta angles can be seen in the final moments of landing. Computer modeling confirmed all these details, showing that ejecta travels at about 1-3 degrees for the most part, but higher than 15 degrees for some particle sizes in the final moments of landing and at higher angles wherever the local terrain modifies the flow of the gas (Lane and Metzger, 2012). The same computer simulations predict a range of velocities for the ejected particles that depends on how large they are, how high the lander is above the surface, the thrust of the lander (which depends on its mass), and how far the particles are from the centerline of the lander at the time they are first lifted (Figure 2). Generally, for Apollo Lunar Module landings, dust particles were shown to travel in the range of 1-3 km/s, while sand particles travelled 100-1000 m/s, gravel around 30 m/s, and larger rocks around 10 m/s (Lane et al., 2010; Lane and Metzger, 2012).

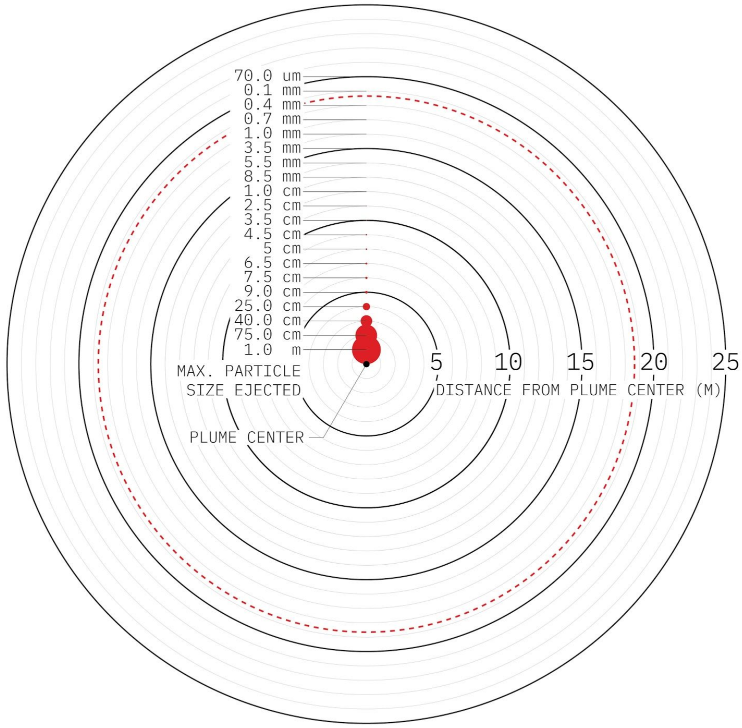


Figure 2: A polar graph showing the size of particles blown (red dots, to scale) as a function of distance from the center of the exhaust plume (concentric rings) for a 40t lander. The dashed line marks the threshold beyond which 126 micron particles cease to be blown. source: Van Susante & Metzger (2016).

The rocket propellant used in the Apollo landings (aerozine and nitrous tetroxide) had an exit velocity of 3.1 km/s, which is higher than lunar escape velocity of 2.4 km/s. Thus, the ejecta (the dust, sand, gravel and rocks that got ejected) from the Apollo landings was dispersed globally on the Moon. Some likely went into orbit around the Sun. The astronauts reported seeing the ejecta travel over the horizon, and analysis shows it then continued on to much higher than orbital altitudes. If methane and liquid oxygen are used instead, then the exit velocity is 3.8 km/s, and if hydrogen and liquid oxygen are used, then the exit velocity is 4.5 km/s. Thus, future landers using these other propellants are expected to blow ejecta faster and farther than before.

The best estimate for how much ejecta was blown with each landing is that about 2.6t of regolith was ejected during each 5t (landing mass) Lunar Module landing (Lane and Metzger, 2015), so scaling at the 2.5 power index (derived from analysis of Apollo landing videos) to a 40t lander implies 470t of regolith would be ejected. However, the much denser plume under such a large lander might transition to the continuum flow behavior, scaling erosion rate only proportional to mass, which implies 21t of regolith will be ejected. It is unclear where or when that transition will occur, so at present the best we can say is that it will likely be between 21t and 470t of ejecta. Another consideration is that after the looser surface material is ejected, the denser soil beneath it will be more resistant to the plume, so this may reduce the ejecta mass. If the higher pressure directly under the nozzle induces bulk shearing of the soil, it is possible the changing conditions will eject much larger masses of soil, and the ejecta will fly up into much higher angles. Until more experimental work is performed and until more data is gathered from larger landers on the Moon, it is not clear how violent the effects will be. This will have implications for design, material choices, and positioning of surface pads and berms.

Risks

Sand-blasting

Ejecta from the landing of Apollo 12 in 1969 passed over Surveyor III due to the topographical coincidence that the Apollo LM was 6m higher in elevation than Surveyor III (1967). Analysis by Immer et al. (2011b) showed that the bulk of ejecta is blown as a thin sheet (Figure 3) and that if Surveyor III would have been in the main ejecta sheet, damage would have been 1000x higher. The paint was thoroughly scoured by impacting dust and the texture was crushed and intermixed with soil particles. Complete coverage of Surveyor III surfaces was achieved. This intermixing of soil changes the thermal characteristics of the paint causing it to fail performance requirements for thermal management. Other materials were sandblasted by simulated lunar soil at low velocity, and they experienced serious degradation due to the highly abrasive nature of un-weathered lunar soil particles (Clegg et al., 2008). This degradation could have serious implications for expensive assets sharing the lunar surface, and conflicts could arise if a landing or takeoff damages other assets.

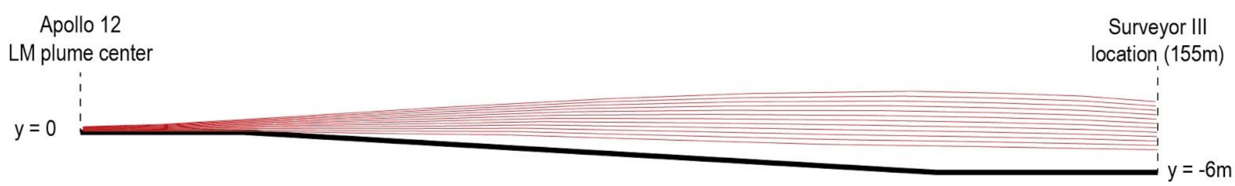


Figure 3: The main “sheet” of ejecta (dust, sand, gravel and rocks) traveling upward at an approximately 1-3 degree slope and away from the landing spacecraft. Surveyor 3 was located beneath the main sheet so was only damaged by a fraction of the impacts that would have occurred if directly exposed. Some ejecta scatters out of this sheet into higher and lower angles. Figure following Tosh, et al., (2011).

Stone-pelting

In the Apollo landing videos, rocks in the size range 4-10 cm were observed blowing at velocities 11-30 m/s, which matched the predictions of computer modeling [Metzger ET al., 2011]. Many “dust tails” a few cm wide and about 15 cm long were observed in these videos. These have been interpreted as partially buried rocks being undercut by the rocket exhaust gas and liberated, releasing the dust tails in the process, although the rocks themselves could not be seen beneath the dense layer of blowing dust. Hence, it was concluded that a large number of rocks were ejected at high velocity during each Apollo landing. Larger landers would blow larger rocks and accelerate them to higher velocities.

Damage to orbital assets

Simulations (Lane et al., 2008; 2010; Tosh et al., 2011; Lane and Metzger, 2012) have shown that the ejecta from the Apollo landings were blown into ballistic trajectories that passed through the orbital altitudes of the Apollo command module and far higher. Recent work in Figure 4 shows the ejecta travel higher than the orbit of the proposed Lunar Gateway. This is a serious concern for future orbital habitats and infrastructure. The Lunar Gateway, a Space station in lunar orbit proposed as the cornerstone of NASA Artemis Program operations, would be especially vulnerable due to its highly eccentric orbit. The relative velocity of ejecta and Gateway at perigee would result in particles impacting at relative velocities well into the hypervelocity regime causing vaporization of both target material and impactor along with a splatter of molten material and additional fracture. Preliminary analysis indicates the Gateway will sustain more than 1 impact/cm^2 across its surface each time it passes through the sheets of ejecta, which could be multiple times before they are dispersed by the solar wind. This will cause erosion of surface materials and coatings which can reduce the efficiency of solar cells, radiators, and thermal control surfaces. It can degrade optics and other instruments ruining their performance. Particulates hitting mechanical joints would roughen the surfaces and inject molten/ re-solidified material creating friction that could cause joints to eventually fail. The effects of impacting dust could make Gateway reach end-of-life or require expensive replacement of solar panels and other components on an unacceptably fast schedule. As lunar surface traffic increases, this could make long-lasting spacecraft in the lunar vicinity impractical.

Possibility of creating an artificial lunar atmosphere

In addition to particle ejecta, exhaust gases are also a phenomenon of concern. The Moon does not possess an atmosphere but rather an exosphere composed of particles that seldom collide. Its total mass is estimated at approximately 25t but each Apollo mission is estimated to have added nearly 10t of gases to the lunar exosphere from engine exhaust alone (Heiken et al., 1991, p.41). While the Apollo gases have by now been eroded by the solar wind, there are concerns about the long-lasting effects that vigorous lunar activity might have on the lunar exosphere or the creation of a long-lasting lunar atmosphere (Vodrak, 1974). An altered lunar exosphere or proto-atmosphere could disrupt scientific objectives and special industrial processes that demand the unique high-vacuum lunar surface environment. While true that most engine exhaust gases are expelled descending from orbit, a spaceport architecture that captures engine exhaust near the surface into a duct and trap system could mitigate part of this risk. Further study is needed to determine how this would compare to the impact of continual leaking and venting of pressurized systems and mining operations that liberate gases.

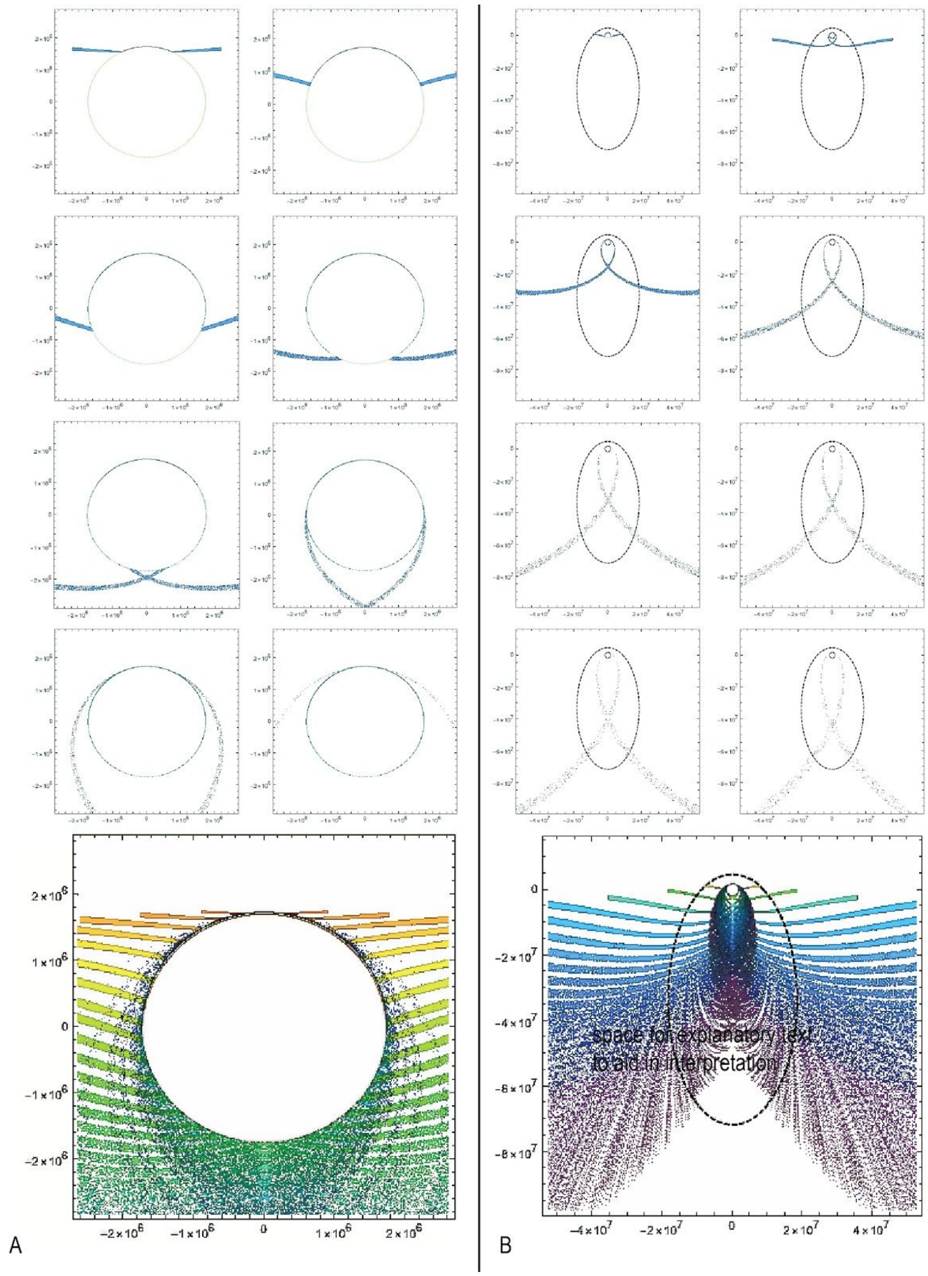
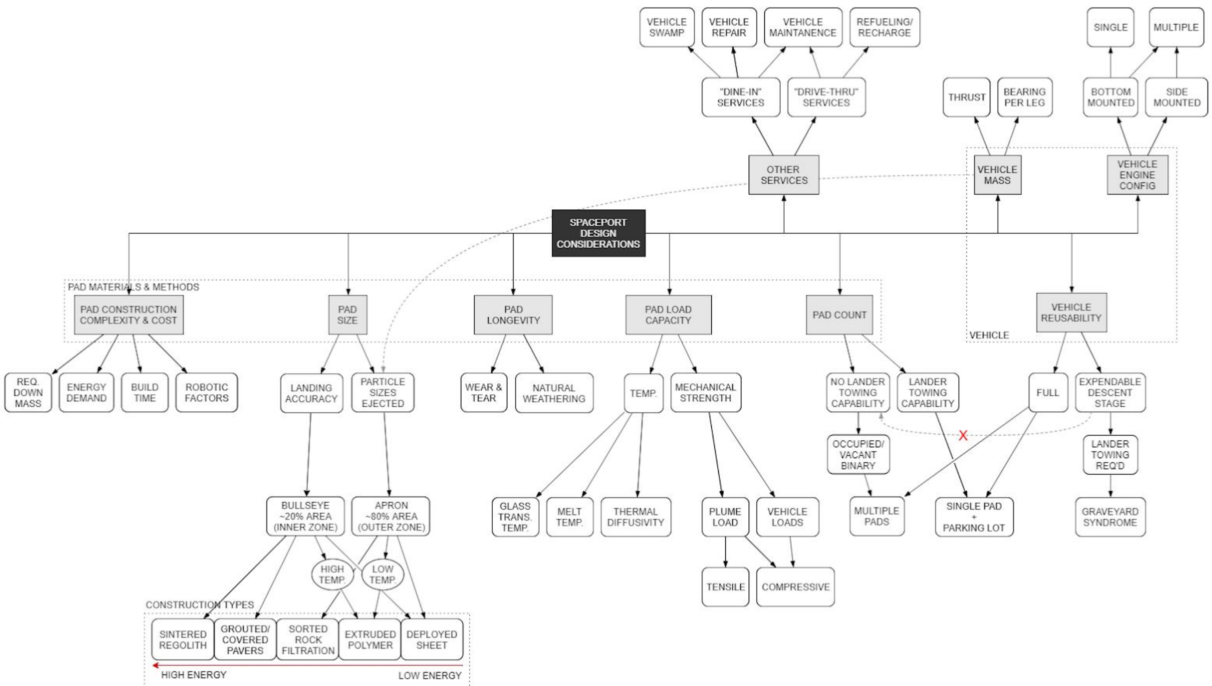


Figure 4A. Sequential images (left to right, top row first) from physics-based computer simulation of ejecta caused by a 40t lunar lander over a period of several hours. Large circle: outline of the Moon. Ejecta encompass the entire Moon and land at every distance.

Figure 4B. Sequential images (left to right, top row first) from physics-based computer simulation of ejecta caused by a 40t lunar lander over a period of several Earth days. Small circle: outline of the Moon. Ellipse: Near Rectilinear Halo Orbit of the Lunar Gateway. Ejecta crosses the Gateway orbit such that Gateway will pass through the ejecta several times before it is dissipated by solar wind.

Design considerations

The global effects of ejecta can be mitigated through the use of landing pads, which can set a unique and positive precedent for shared infrastructure that benefits all lunar actors. Figure 5 attempts to map the design considerations of a spaceport into three categories: pad materials and methods, vehicle, and other services.



Pad count and size

Discussion on the number of landing pads required is a function of how many landers will be parked at a spaceport at a given moment, whether landing vehicles are fully reusable, and whether towing capabilities exist. A pad's overall diameter can be prescribed by understanding the likelihood of different particle sizes being ejected at different distances from the exhaust plume. Work by Van Susante and Metzger (2014) using an analytical model set the minimum diameter of a landing pad for a 40t lander at 18.8m. Their results have been mapped in Figure 2. Due to the radial dissipation of plume pressure, they determined that at a certain distance from the plume (18.8m), the particles most susceptible to erosion are no longer erodible. Beyond plume effects, pads must also be large enough to allow for deviation in landing accuracy. Landing pad dimensions may naturally decrease as more accurate and precise landing technology comes online.

Pad capacity and longevity

The primary loads on a pad when in use come from the high temperatures in the plume jet and from the mechanical pressure imparted by the plume, the footpads of the ascent/descent vehicle and the wheels of other vehicles that may service the spaceport or landing vehicle. Plume mechanical loads are not fully characterized, but it is evident from previous work that this is a dynamic load determined by the vehicle. Pads must also be designed to survive ambient lunar weathering when not in use. Parts of the lunar surface experience daily thermal changes in excess of 500°C. Structures in contact with the surface will have to contend with differences in thermal properties including rates of thermal expansion during the day/night transition. Ultraviolet radiation degrades materials through photooxidation, which break molecular chains in a variety of materials. The routine practice of maintenance and repair, both for use wear-and-tear and weathering, must be built into the design of any spaceport.

Pad construction and bootstrapping

There are promising materials and techniques being developed that could withstand expected loads outlined in Figure 5 and expounded upon in depth in the literature. It is worth noting that the impossibility of replicating the lunar vacuum, lunar gravity and the lunar thermal environment simultaneously on Earth means that a “winning method” will remain unknown until after extensive testing on the Moon itself. Of course, getting to a place of regular launch and landing will itself require landing pads. This classic bootstrapping problem driven by the need to mature technology, conduct at-destination testing, managing risk, and maximizing utility under strict payload budgets, is steep but can be overcome. As engineers progress these issues in terrestrial labs, the rapidly developing lunar launch services sector, especially the development of super-heavy (100t) lift vehicles, suggest that the long-held aversion to transporting mass from Earth may diminish. As such, mission planning “down to the gram” may soon no longer be necessary or desirable, allowing mission planners to engage seriously with ideas for large-scale civil engineering projects.

Vehicle mass and engine configuration

A vehicle’s mass, its maximum thrust, number and configuration of its engines, throttling and ignition behavior, and weight distribution on its footpads will determine live loading on the pad. The part of the pad beneath the engine nozzle(s) must be impenetrable to gases or risk tensile failure caused by an “inflating” of the pad form below. As the industry transitions towards ever-heavier vehicles, it may become necessary to co-evolve engine configurations to be further away from the ground and canted outwards, reducing pad loading.

Policy and Operational Considerations

The environmental factors associated with increased lunar activity present in a number of key areas: physical damage (gravel strikes, debris, particle impacts, vaporization/holes); compromise of solar panel and other coatings through erosion, cracking, pitting; thermal effectiveness, human safety in orbit and on the surface (suit punctures, joint wear and tear, orbital habitat damage); and atmospheric contamination. These factors have both spatial and temporal dimensions to them, which introduce considerations for operating models as well as norms of behavior and formal policy making.

As we have seen, there are global-scale interdependencies associated with the introduction of new material into the exosphere. Sand blasting and dust tails have implications for proximity operations and safety zones, which in turn provide considerations for the design of any future property management regimes such as priority rights (see below). Although it may seem that they are independent of each other, each of these domains influence the realities within which regular activity would be carried out.

Location

Installation of a spaceport requires site selection which involves a sustained occupation of that site. The primary relevant legal framework for space activities is the Outer Space Treaty (OST) which does not address questions of surface coordination or authority over occupancy. The Hague Space Resources Working Group recently introduced a set of proposals for an international framework which would provide for the international recognition of what are called “priority rights” for operators. These priority rights would apply “for a maximum period of time and a maximum area upon registration in an international registry.” Although these guidelines are designed with an emphasis on resource utilization, they are an example of the kinds of practical frameworks beginning to be explored. As the design and durability of spaceports clarify, these factors would mix with the designation of any “maximum period of time” designated for priority rights and require that such time period is long enough to amortize the necessary financial investments.

The regional placement of landing pads will be a function of mission design and goals. They will need to be proximal to the site of mission activities but may also conflict with or restrict access to those sites at some times. This may be especially pertinent or sensitive around scarce resources, such as the “Peaks of Eternal Light.” Managing access will require at least some minimal coordination mechanisms between users. A relevant precedent is the failure of “big sky theory” in aviation (Raymond, 1997 p.8). As aviation activity increased, there were incidents of aircraft colliding in midair in the 1950s. In addition, the concentration of use required to support the massive financial cost of airport construction has led to airports as massive hubs of activity which are independently financed, and of course involve coordination mechanisms around access and use. We would be remiss to think that the same will not be necessary for other planetary bodies.

Public Goods

It may be natural to think of landing pads as private assets controlled by individual actors. However, the global interdependencies introduced by the ability for a single actor to subtract from others’ use of the exosphere, suggest that many of the incentives around use and management of spaceports may be best understood in the context of a Common Pool Resource[1]. In economics this is a type of good that, despite being subtractable, is difficult to control or limit access to. On the Moon, access to a landing pad would be a way to mitigate the negative externalities of exospheric contamination, and thus arguably be in the interests of all actors. This could be seen as an argument for landing pads as publicly funded as opposed to private endeavours: if such technology is made available to all, the benefits also accrue to all. In this sense these open designs would themselves be public goods-- accessible to anyone, but also non-subtractable.

Associated capabilities such as precision landing and even research regarding the dynamics of the dust would support actors’ ability to behave responsibly, but developing this knowledge might be quite expensive. The first batch of commercial operators targeting the lunar surface today are working on precision landing[2] but at the moment those capabilities are considered experimental and are untested. Meanwhile their stated landing accuracies in

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[1] Schlager, E., & Ostrom, E. (1992). Property-Rights Regimes and Natural Resources: A Conceptual Analysis. *Land Economics, 68*(3), 249-262. doi:10.2307/3146375

[2] NASA Awards Intuitive Machines $1.3 Million Tipping Point Partnership, September 23, 2019. http://spaceref.com/news/viewpr.html?pid=54701

customer literature are in the ~2km range, which is not accurate enough to make use of landing pads even if they did exist.

As we begin to understand the requirements of responsible behavior, will it be acceptable to limit access to the lunar surface for those actors who do not act responsibly? What about actors who wish to act responsibly but do not have the means? If a requirement or norm arises around the use of landing pads, how can the benefit sharing provisions of the Outer Space Treaty be protected? We may see a tension between control and access, especially for less affluent actors. The introduction of openly licensed public goods could help to mitigate some of these challenges.

Given the remoteness of the Moon, the large costs associated with lunar missions, and the shared interest in increased activity, some may even wish to go further in developing norms of behaviour that recognize when actors need access to a landing pad. Such norms would find at least some legal precedent in the Astronaut Rescue Agreement[3], which obligates states parties to the treaty to extend assistance even when that assistance is otherwise beyond their jurisdictional responsibility.

Safety zones and proximity operations

Modeling as discussed above has shown that even small landers on the order of 1t create ejecta which travels for tens of kilometers. As a reference point, Astrobotic's Peregrine lander (scheduled to launch to the Moon in July 2021) has a wet mass of 1,313 kg[4], suggesting that this ejecta will be a consideration for all weight classes of lunar lander. The development of a lunar market will eventually require proximity operations for the development of infrastructure and services. Small actors, more dependent on market dynamics than the large class lunar spacecraft such as Blue Origin and SpaceX, will have the earliest incentive to solve the challenge of proximity, but also the least amount of disposable resources to invest in infrastructure not directly related to their business model. This is another case where mechanisms for cost-sharing or public goods provision could help to stabilize or accelerate lunar activity.

Such considerations are one of the many factors influencing a growing interest in the definition of safety zones, and protocols for proximity operations. Landing pads could significantly reduce the necessary size of safety zones, but the all-encompassing, global nature of lunar ejecta will render the task of defining these safety zones somewhat arbitrary until the relationship between the parameters of lander designs are matched with their ejecta profiles. Due to the difficulty of simulating complex granular interactions and the impossibility of faithfully reproducing the lunar environment on Earth, these relationships can only be determined accurately after empirical tests on the lunar surface. Until we understand these better, such "safety zones" may even be abused as grounds for control over a territory.

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[3] Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, UN Office of Outer Space Affairs, 1967. Accessed Nov. 1, 2019. https://www.unoosa.org/pdf/gares/ARES_22_2345E.pdf

[4] Astrobotic Payload Users' Guide, https://www.astrobotic.com/payload-user-guide, accessed November 20, 2019.

Transparency
The need for coordination between actors, the management of liability and responsibility, and the Outer Space Treaty itself adds the requirement for active transparency. Information about where, when and for how long an activity will be undertaken will need to be accessible in such a way that other actors can plan for dust and disturbances; or, to coordinate landings and site occupancy. Today the United Nations Office of Outer Space Affairs manages a basic registry for space objects, but there are growing endorsements of the idea of an enhanced registry which could reflect increasingly dynamic activities and the distinct transparency challenges of future surface activity on other planetary bodies. Will private actors submit their landing requests to national authorities, and wait for it to be passed along to the United Nations before undertaking that action? There is clearly a threshold of activity for which this would no longer be practical.

Cost
Norms around access and sharing might also have implications for how landing pads are developed and financed. As the engineering science for lunar landing pad construction develops, construction time, operating lifespan, and capital investment requirements will be clarified. If landing pads turn out to be (relatively) expensive to construct, it may become advantageous to concentrate other services around them, which in turn would increase costs and create more incentive for commercial services or shared investment models.

To the extent that the lunar environment is a global good, public funding (which is not currently well-defined in the lunar context), may be appropriate. In this case, what, if any, would be the rights or obligations of use? How would contention over its access and use be addressed, and what kinds of actors (State, private) would be recognized in such a system?

Conclusions

Dust will be a significant issue to manage on the lunar surface. Without the ability to put things in proximity to one another, we undermine the ability to provide (and consume) infrastructure and services, which are a necessary condition for the development of the lunar ecosystem. While there is still much to be learned about the nature and dynamics of ejecta and exhaust, we do know that the environmental risks and impacts will be global in nature. This provides a case study for the role of open design and engineering and introduces a new category of public goods as considered in the lunar context. Combined with insights about the technical considerations for landing pad design, this paper provides new information to inform discussions about institutional models and coordination mechanisms that may be required to finance and operate these important pieces of infrastructure in the future.

References

Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, UN Office of Outer Space Affairs, 1967. Accessed Nov. 1, 2019

Astrobotic Payload Users' Guide, https://www.astrobotic.com/payload-user-guide, accessed November 20, 2019.

J. O. Elliott, B. Sherwood, A. Austin, M. Smith, R. Polit-Casillas, A. Scott Howe, G. Voecks, A. Colaprete, P. Metzger, K. Zacny, V. Vendiola, "ISRU in Support of an Architecture for a

Self-Sustained Lunar Base", International Astronautical Congress IAC2019, Washington DC, USA, 21-25 October 2019.

BBC News, Private plan to send Moon rover to Apollo 17 site. Nov. 30, 2016. https://www.bbc.com/news/science-environment-38163327

Clegg, Ryan N., Philip T. Metzger, Stephen Huff, and Luke B. Roberson (2008). "Lunar soil erosion physics for landing rockets on the Moon," paper no. 4122, Lunar Exploration Analysis Group (LEAG) 2008 Annual Meeting, Cape Canaveral, FL.

Cockell, C., "Freedom Engineering – Using Engineering to Mitigate Tyranny in Space". Space Policy 49, August 2019

Heiken, Grant H., David T. Vaniman, and Bevan M. French (1991). *Lunar Sourcebook-A User's Guide to the Moon.* Cambridge, England: Cambridge University Press.

Immer, Christopher D., John E. Lane, Philip T. Metzger, and Sandra Clements (2011a). Apollo Video Photogrammetry Estimation of Plume Impingement Effects. *Icarus* 214: 46–52

Immer, Christopher D., Philip Metzger, Paul Hintze, Andrew Nick and Ryan Horan (2011b). Apollo 12 Lunar Module Exhaust Plume Impingement on Lunar Surveyor III. *Icarus* 211(2): 1089-1102.

Lane, John E., and Philip T. Metzger (2012). Ballistics Model for Particles on a Horizontal Plane in a Vacuum Propelled by a Vertically Impinging Gas Jet. *Particulate Science and Technology* 30(2): 196-208.

Lane, John E. and Philip T. Metzger (2015). Estimation of Apollo lunar dust transport using optical extinction measurements. *Acta Geophysica* 63 (2): 568-599.

Lane, John E., Philip T. Metzger, and Jeffrey W. Carlson (2010). Lunar Dust Particles Blown By Lander Engine Exhaust in Rarefied and Compressible Flow. *Earth and Space 2010: Engineering, Construction and Operations in Challenging Environments*, Honolulu, HI.

Lane, John E., Philip T. Metzger, and Christopher D. Immer (2008). Lagrangian trajectory modeling of lunar dust particles. Earth & Space 2008: Engineering, Construction and Operations in Challenging Environments, Long Beach, CA.

Metzger, Philip T. (2016). Rocket Exhaust Blowing Soil in Near Vacuum Conditions is Faster than Predicted by Continuum Scaling Laws. *Earth and Space 2016: Engineering, Science, Construction, and Operations in Challenging Environments*, Orlando, FL

Metzger, Philip T., Christopher D. Immer, Carly M. Donahue, Bruce T. Vu, Robert C. Latta, III, Matthew Deyo-Svendsen (2009a). Jet-induced cratering of a granular surface with application to lunar spaceports. *J. Aerospace Engineering* 22 (1): 24-32.

Metzger, Philip T., John E. Lane, C.D. Immer, J.N. Gamsky, W. Hauslein, Xiaoyi Li, R.C. Latta III, C.M. Donahue (2010). Scaling of Erosion Rate in Subsonic Jet Experiments and Apollo Lunar

Module Landings. *Earth and Space 2010: Engineering, Construction and Operations in Challenging Environments*, Honolulu, HI.

Metzger, Philip T., Robert C. Latta III, Jason M. Schuler, and Christopher D. Immer (2009b). Craters Formed in Granular Beds by Impinging Jets of Gas. *Proceedings of Powders and Grains 2009*, Golden, Colorado..

Metzger, Philip T., Xiaoyi Li, Christopher D. Immer, and John E. Lane (2009c). ISRU Implications of Lunar and Martian Plume Effects. *Proceedings of 47th AIAA Aerospace Sciences Conference*, Orlando, FL.

Metzger, Philip T., Jacob Smith, and John E. Lane (2011). Phenomenology of soil erosion due to rocket exhaust on the Moon and the Mauna Kea lunar test site. *Journal of Geophysical Research: Planets* 116, no. E6.

NASA Awards Intuitive Machines $1.3 Million Tipping Point Partnership, September 23, 2019. http://spaceref.com/news/viewpr.html?pid=54701

O'Neill, Ian (2012), "Mars Shot First: Curiosity's Wind Sensor Damaged", https://astroengine.com/2012/08/21/mars-shot-first-curiositys-wind-sensor-damaged/.

Raymond, J.W., "Airports and Spaceports: A Historical Comparison," The Research Department, Air Command and Staff College, 1997.

Roberts, Leonard (1963). The Action of a Hypersonic Jet on a Dust Layer. IAS Paper No. 63-50 (New York: Institute of Aerospace Sciences 31st Annual Meeting).

Schlager, E., & Ostrom, E. (1992). Property-Rights Regimes and Natural Resources: A Conceptual Analysis. *Land Economics, 68*(3), 249-262. doi:10.2307/3146375

Tosh, Abhijit, Peter A. Liever, Robert R. Arslanbekov, and Sami D. Habchi (2011). Numerical analysis of spacecraft rocket plume impingement under lunar environment. *Journal of Spacecraft and Rockets* 48(1): 93-102.

Vondrak, R. (1974). Creation Of An Artificial Atmosphere On The Moon. *Nature* 248(5450): 657.