NASA (2015). *Good night, Moon.* Available at: https://www.nasa.gov/image-feature/good-night-moon.

Concepts for an In-Situ, Reusable Construction System for Lunar Landing and Launch Pads

Pascal Rodel – PhD Student, Center for Space Resources – rodel@mines.edu

Liz Scott – PhD Student, Center for Space Resources – eascott@mines.edu

Ben Thrift – PhD Student, Center for Space Resources – benthrift@mines.edu

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Increasing Lunar Activities

- Civil and commercial space activities on the Moon are expected to increase in the coming years
- Landing areas may be closely-spaced
  - Areas of common commercial interest, such as the South Pole
  - Establishing commercial enterprises may require multiple landings in the same area
    - For example, water propellant extraction could require harvesters, processors, storage tanks, etc.

Vaughan, J (2017). ROOM: The Space Journal. https://room.eu.com/

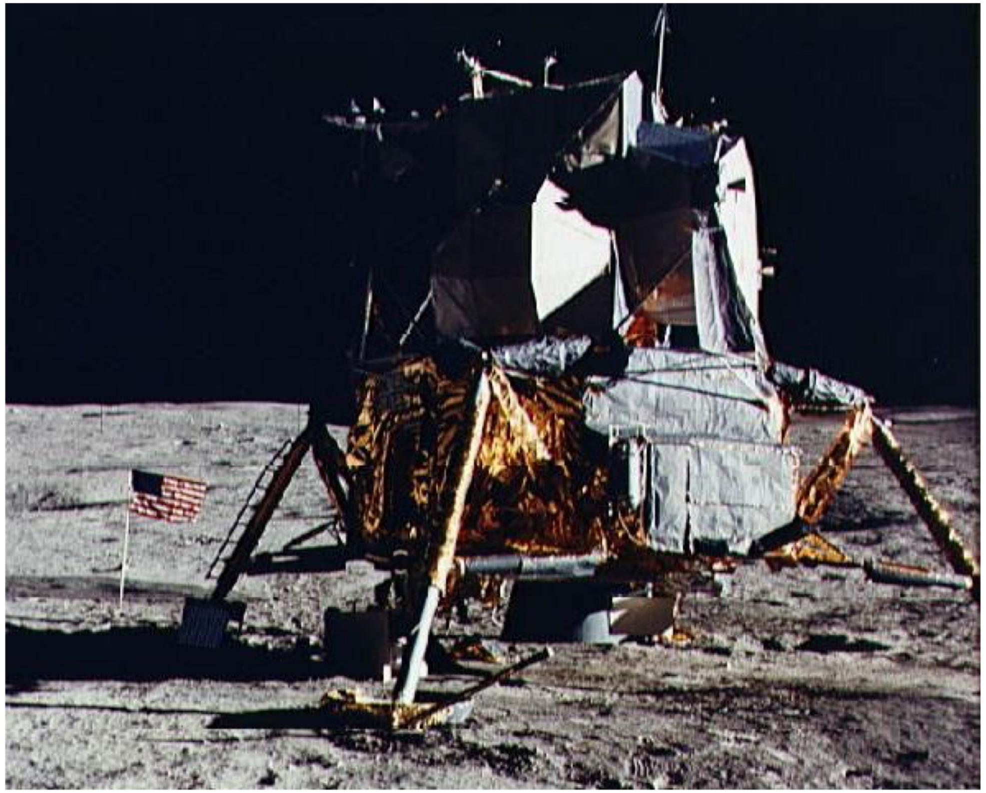
The Problem with Regolith

- Landing and launch operations produce high-velocity, fine, abrasive particles
  - Can cause damage to nearby hardware and infrastructure
  - Could disturb nearby resources, historic sites, or scientific sites
  - Particles can even be ejected into Lunar orbit, causing damage to incoming landers or orbiting spacecraft

Lane, J., and Metzger, P., "Estimation of Apollo Lunar Dust Transport using Optical Extinction Measurements", Acta Geophysica, vol. 63, no. 2, pp. 568-599, 2015

The Need for Pads

- Landing and launch pads can reduce or mitigate regolith ejecta
- Landing pads can also provide a safe, smooth, navigable landing surface for landers
  - Reduces risk to landing spacecraft



Williams, D.R. (2019). Apollo 14 Lunar Module /ALSEP. NSSDCA/COSPAR ID: 1971-008C, available at https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1971-008C

System Objectives

Landing/Launch Pad

- Reduce or eliminate ejecta during landing or launching
- Withstand spacecraft forces
- Allow reuse
- Survive the Lunar environment
- Enable site location by incoming spacecraft

Construction System

- Construct infrastructure
- Verify completed infrastructure
- Deployable in a single launch
- Native power system
- Survive the Lunar environment
- Require minimal processing of regolith

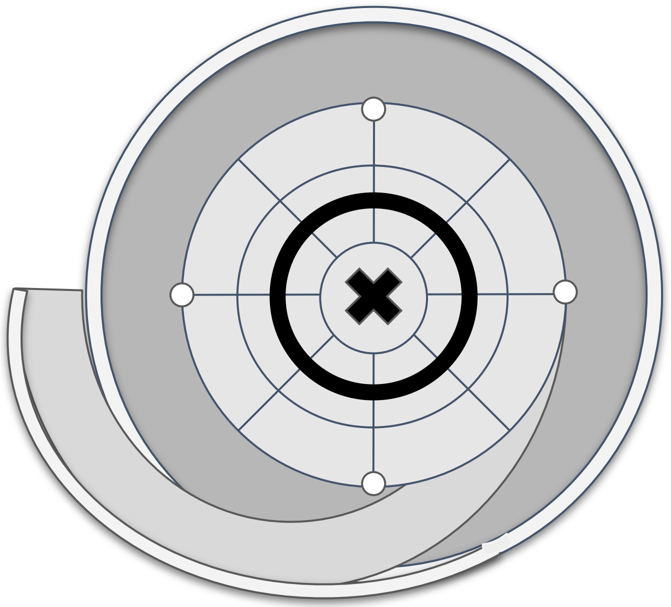
System Selection

- Based on these objectives, the best architecture is:
  - A pad made of regolith sintered with microwaves
    - In-situ microwave sintering requires very little processing of the regolith
    - Microwaves can be tuned to sinter regolith below the surface
  - A construction system based on JPL's ATHLETE robot
    - ATHLETE design is at a fairly high TRL
    - Flexibility of ATHLETE architecture allows construction of 3D pad features, swappable tools, ability to inspect completed pad

Taylor, L.A. and Meek, T.T. (2005). Microwave Sintering of Lunar Soil: Properties, Theory, and Practice, Journal of Aerospace Engineering, 2005, 18(3), pp 188-196

Preliminary Landing Pad Design

- Pad diameter of 15 m x 0.5 m deep
  - Approximately 3x the size of CLPS-class landers
- Seams for thermal expansion and stress relief
- Ejecta shield to contain excess dust and ejecta
- Lightly sintered dust mitigation area between pad and ejecta shield
- Egress point for construction robot and spacecraft
- Landing beacon
- Optical target markings and reflectors



Launch Pad Design Concepts

- Launch pad infrastructure is more involved than landing pad
  - Thermal loading is higher due to spacecraft engine ignition on surface
  - Additional mechanisms, such as fuel lines and verticators, may also be necessary
- Sintered regolith can be used to construct launch pad structure
  - Will likely require additional thermal mitigation features and exhaust chutes

The ATHLETE Architecture

- ATHLETE is a six-limbed rover chassis
  - Each limb is equipped with a wheel and camera
  - Each limb can articulate individually
    - Rolling traverse, walking, or precision motion
- ATHLETE would be equipped with on-board power, sensor suite, and construction tool kit
- Construction and inspection will be performed autonomously or by teleoperators

Wilcox, B.H., Litwin, T, Biesiadecki, J, Matthews, J, Heverly, M, Morrison, J. (2007). ATHLETE: A Cargo Handling and Manipulation Robot for the Moon. Journal of Field Robotics 24(5), 421–434, Wiley Periodicals, Inc

The Lander

- Construction architecture will also include a lander for the ATHLETE robot
- The Lander will:
  - Act as the interface between the ATHLETE and the launch vehicle
  - Protect the ATHLETE during cruise to the Moon
  - Provide landing and deployment capabilities for the ATHLETE on the Lunar surface
  - Act as thermal protection for the ATHLETE during the Lunar night
  - Generates power and provides charging for the ATHLETE
  - Act as a communications relay between ATHLETE and teleoperators

Concept of Operations

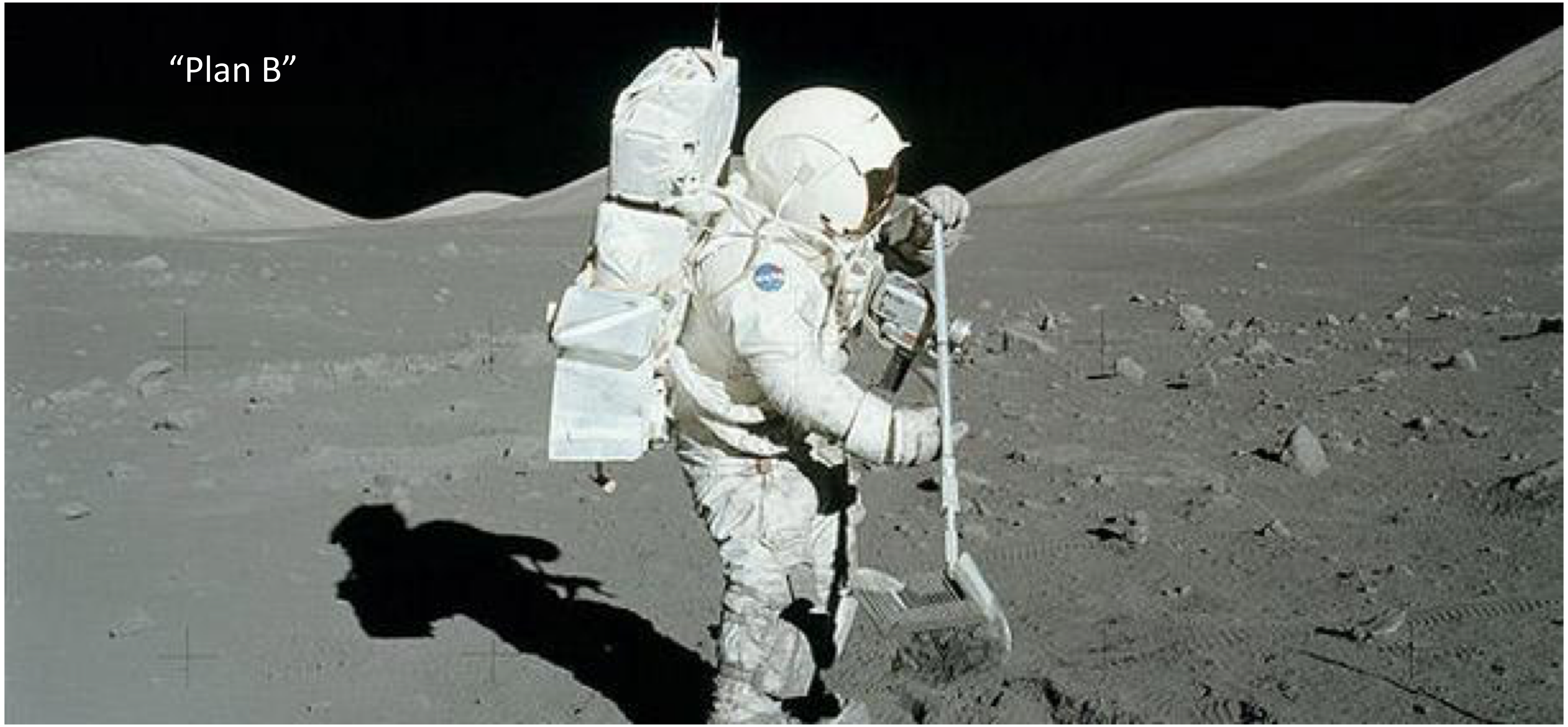
- Lander and ATHLETE deploy on Lunar surface
- ATHLETE inspects and prepares landing area
- ATHLETE sinters landing area and constructs berms
    - Pad sintering will take ~6 months of sunlight
- ATHLETE inspects and repairs pad before and after each spacecraft landing
- ATHLETE returns to Lander as needed for thermal protection and battery charging

A. Howe, S., Wilcox, B., Mcquin, C., Townsend, J., Rieber, R., Barmatz, M., Leichty, J. (2013). Faxing Structures to the Moon: Freeform Additive Construction System (FACS). AIAA SPACE 2013 Conference and Exposition. 10.2514/6.2013-5437

Future Work

- Quantify mechanical properties of sintered Lunar regolith
  - Preferably actual regolith from polar regions
  - Verify feasibility of sintering at depth
- Further launch and landing pad design and perform scale tests to verify strength and thermal characteristics and ejecta mitigation
- Further the design of the ATHLETE and perform functional tests in regolith simulant
- Further the design of the Lander and perform functional tests

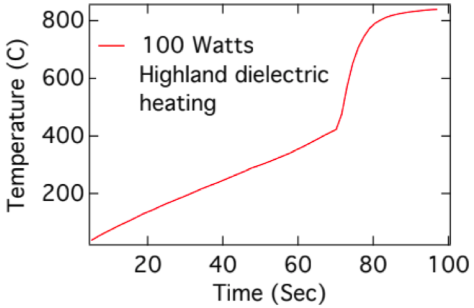
Questions?

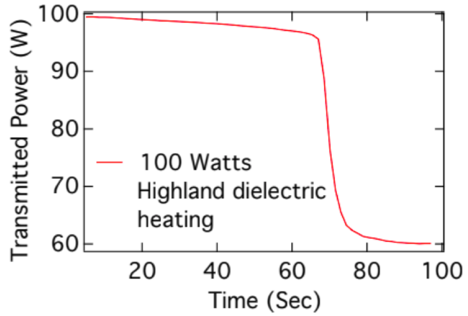


NASA (1972). Apollo 17 photograph AS17-134-20425. Available at: https://www.lpi.usra.edu/lunar/samples/apollo/tools/

Power Analysis for Regolith Heating

- Heating versus input power increases sharply at around 400^{O}C
  - Exploring possibilities for preheating regolith
- Input power to sinter pad with drop to 60% power at 400°C
  - 15 m diameter, 0.5 m deep pad
    - Approximately 160 Tonnes of Regolith
    - Heating from 100°C to 1250°C
      - 12.9 kW with 6 months of light
      - Assuming: No depth loss, 70% Electrical to Microwave efficiency, 1.8 g/cc Regolith Density, 1100 J/kg*K Average Specific Heat





[Barmatz]

Strength Analysis

Maximum Pressure: 84 MPa

Green: Pressure Well Below Maximum

Yellow: Pressure Above Half Maximum

Red: Pressure Over Maximum

Velocity After Breaking (m/s)	Thruster Cutoff Height (m)	Impact Velocity (m/s)	KE @ 5000 kg (kJ)	Impact Force @ 12.5 cm Compression (kN)	Pressure @ 0.5 m^2 Contact Area (MPa)
1	100	18.00	810	6480	12.96
2	100	36.00	3240	25920	51.84
3	100	54.00	7290	58320	116.64
4	100	72.00	12960	103680	207.36
5	100	90.00	20250	162000	324
1	50	12.73	405	3240	6.48
2	50	25.46	1620	12960	25.92
3	50	38.18	3645	29160	58.32
4	50	50.91	6480	51840	103.68
5	50	63.64	10125	81000	162
1	30	9.86	243	1944	3.888
2	30	19.72	972	7776	15.552
3	30	29.58	2187	17496	34.992
4	30	39.44	3888	31104	62.208
5	30	49.30	6075	48600	97.2
1	10	5.69	81	648	1.296
2	10	11.38	324	2592	5.184
3	10	17.08	729	5832	11.664
4	10	22.77	1296	10368	20.736
5	10	28.46	2025	16200	32.4

Notes:

Impact force applies on the lander

Assumption that entire 0.5m^2 lander contacts the pad at once

Analysis is first-order approximation

Thermal Analysis

Operating environment

- Lunar surface day temperatures:
  - 0° latitude: 193°C
  - 30° latitude: 107°C
  - 60° latitude: 58°C
  - 75° latitude: 8°C
- Lunar surface night temperatures:
  - 0° latitude: -150°C
  - >85% latitude: -233°C

Available technology

- Low temperature electronics
  - -55°C to +125°C (COTS)
  - No issue for lunar day operations
- Space qualified batteries
  - -50°C to 40°C
  - Current research into high temperature batteries (Solid State Ceramic Oxide) with operating temperatures > 400°C
- Michelin Tweel (special purpose wheel)
  - -233°C to °125°C

Note: Analysis is a first-order approximation

Thermal Analysis

Operating Summary

- ATHLETE rover can operate normally during lunar days
- ATHLETE rover has limited resistance to high bandwidth thermal cycles

Thermal requirements

- ATHLETE rover needs to be functional after lunar night
- Thermal cycling to be limited to ensure appropriate life expectancy of rover

Potential solutions

- Thermal protection doghouse coupled with Advanced Stirling Radioisotope Generator (ASRG) or other heat sources
- Heated Lunar ground penetrator power storage (Ulamec, 2010)

Preliminary Analysis

- First analysis indicates best strategy is to "wake up" rover, not heat & insulate

Note: Analysis is a first-order approximation