Lunar Infrastructure for Landing and Launch Risk Mitigation

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Introduction

To prepare for human exploration missions to Mars, NASA is planning to demonstrate surface operations initially on the Moon. These operations may include:

- Human Crew on the lunar surface by 2024
- Teleoperation of surface assets from orbit (Gateway)
- Sample return from the lunar surface
- Surface power technology demonstrations
- Communications delay and autonomous operations
- Establishing deep space logistics supply chains
- In-Situ Resource (ISRU) demonstration missions

Delta Clipper "DC-X" Flight Video - 1996 (McDonnell Douglas / NASA)

https://www.youtube.com/watch?v=o2sHf-udJI8

https://www.youtube.com/watch?v=JzXcTFfV3Ls

https://www.youtube.com/watch?v=Kk-gGtC7xZ4

Landing 1 & Landing 2

https://www.airspacemag.com/space/black-day-at-white-sands-1381694/

http://www.b14643.de/Spacerockets/Specials/DC-X_DeltaClipper/index.htm

Armadillo Aerospace "Pixel" Flight Video – 2008
NASA Centennial Lunar Lander Challenge

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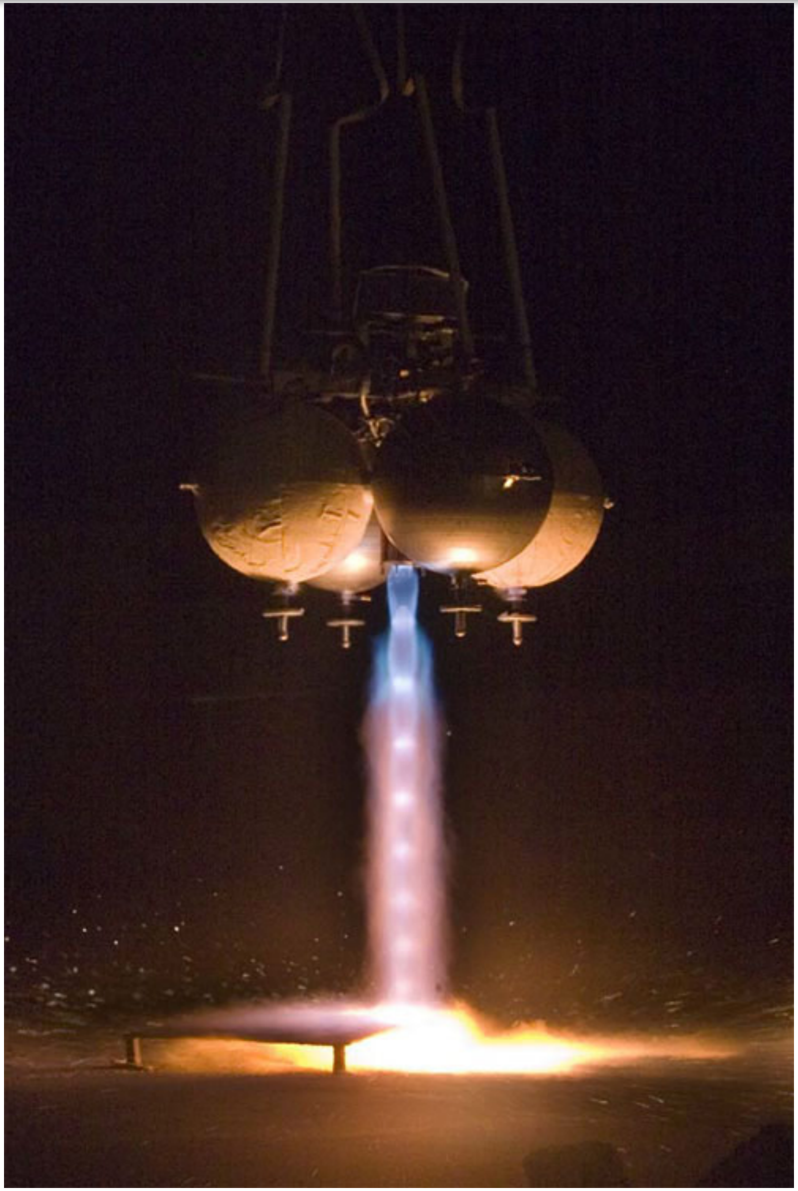
Edited Videos\Qualification Flight.mpg

https://upload.wikimedia.org/wikipedia/commons/e/ec/Armadillo_Aerospace_Pixel_Hover.jpg



Masten Aerospace “Xombie” Flight Video - 2014

https://www.youtube.com/watch?v=f_GZvygaEH4
https://www.youtube.com/watch?v=53hLiOWHByQ

Launch & Landing

Blue Origin "New Shepard" Flight Video - 2015

https://www.youtube.com/watch?v=YUzYCDbDInc

Launch & Landing

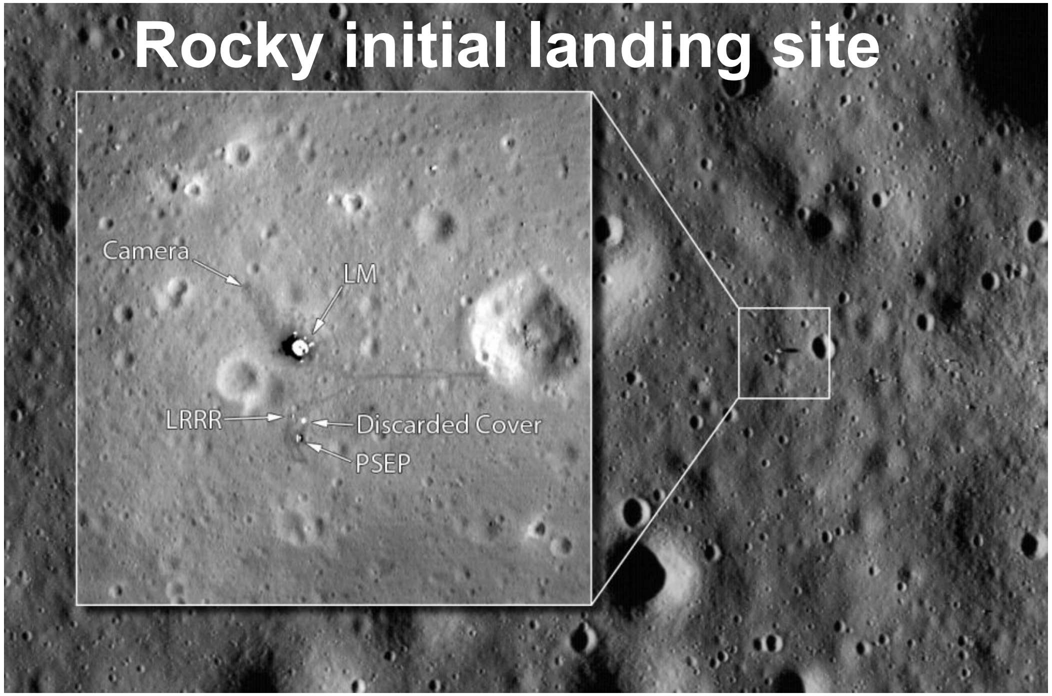
https://spacenews.com/blue-origin-reaches-space-again-on-latest-new-shepard-test-flight/

SpaceX "Falcon 9 First Stage" Flight Video - 2015

https://www.youtube.com/watch?v=I5I8jaMsHYk Landing

Apollo 11 - Close Call

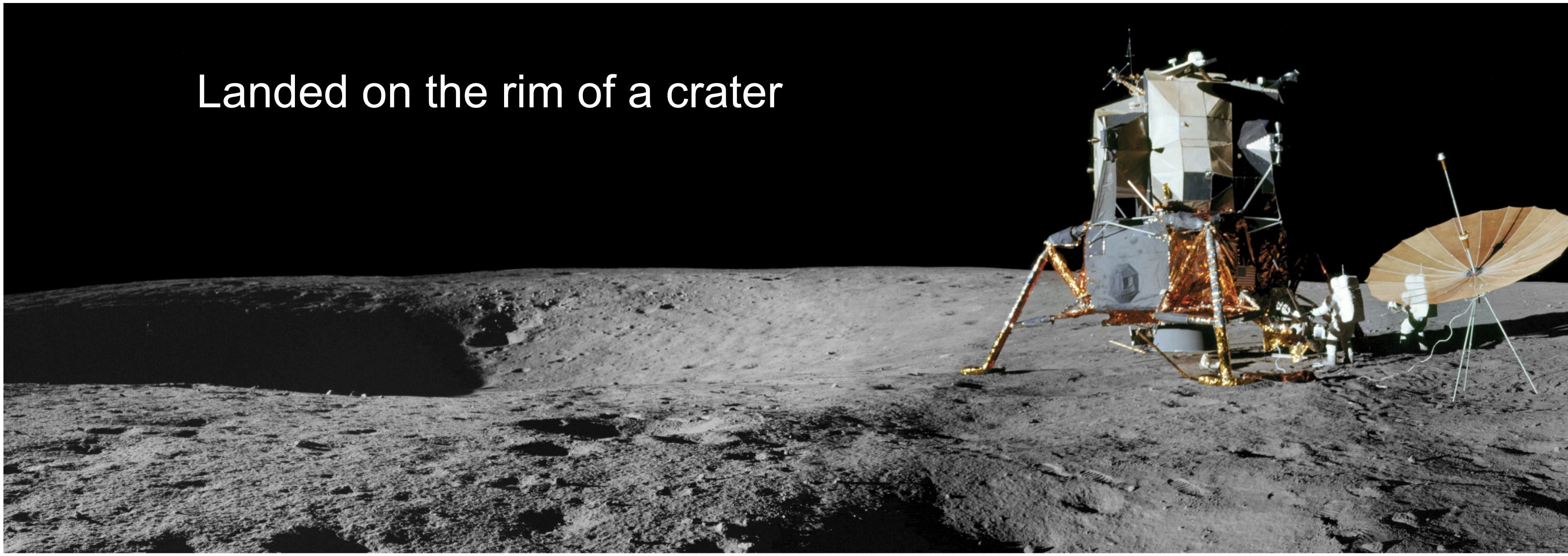
Observed Armstrong during the Technical Debrief: "…at something less than 100 feet; we were beginning to get a transparent sheet of moving dust that obscured visibility a bit. As we got lower, the visibility continued to decrease."



On the very first Apollo landing, the surface features were prominently displayed, just not the right kind in the right place. At 1,500 feet above the Sea of Tranquility Neil Armstrong saw the kind of surface features an Apollo commander does not want to find in his landing zone. Said Armstrong during a 1969 Technical Debrief: "…we were landing just short of a large rocky crater surrounded with a large boulder field with very large rocks covering a high percentage of the surface."

https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

Apollo 12 – Close Call



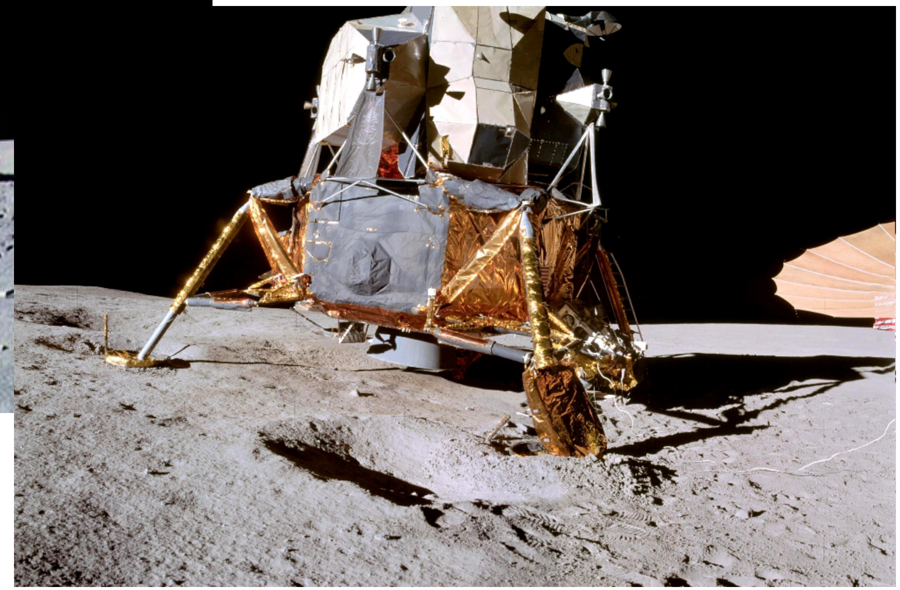
Apollo 12, Ocean of Storms, EVA 1, 19 November 1969, frames A12-46-6746 to A12-46-6751 : Apollo 12 landing site showing the deep shadow on the eastern wall of Surveyor C

On Apollo 12, Pete Conrad encountered so much dust that his final descent to the surface was done in the blind. Said Conrad in a 1969 Technical Debrief:

"The dust went as far as I could see in any direction and completely obliterated craters and anything else… I couldn't tell what was underneath me. I knew I was in a generally good area and I was just going to have to bite the bullet and land, because I couldn't tell whether there was a crater down there or not."

Apollo 14 - Close Call

https://www.hq.nasa.gov/alsj/a14/a14.landing.html



"In one respect an Apollo lunar module is like a pinball machine -- it doesn't like to tilt," said Epp (JSC Project Manager for ALHAT),"If a lunar module came to rest at an angle beyond 12 degrees tilt the astronauts might not be able to launch themselves off the surface. So if a crew landed on a hill or with a footpad or two on a large rock or in a crater, that could make for a bad day."

https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

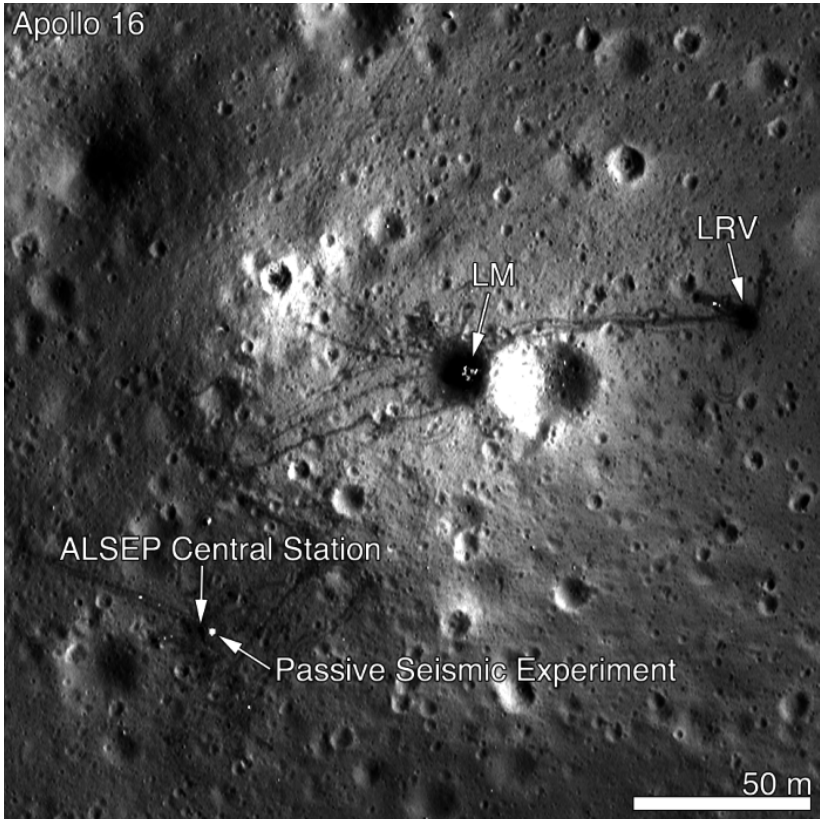
Apollo 15 – Close Call

Below about 60 feet (18 m), Scott could see nothing of the surface because of the quantities of lunar dust being displaced by Falcon's exhaust

Apollo 15's lunar module Falcon came to rest with its rear footpad on the rim of a 20-foot-wide crater. This caused one of the lunar module's footpads to be off the surface entirely and placed the spacecraft at an 11-degree tilt. Stated Scott in the mission's debrief -- "…at the altitudes looking down as we approached the landing, it was very difficult to pick out depressions… as far as the shallow depressions there and the one in which the rear footpad finally rested, I couldn't see that they were really there. It looked like a relatively smooth surface."

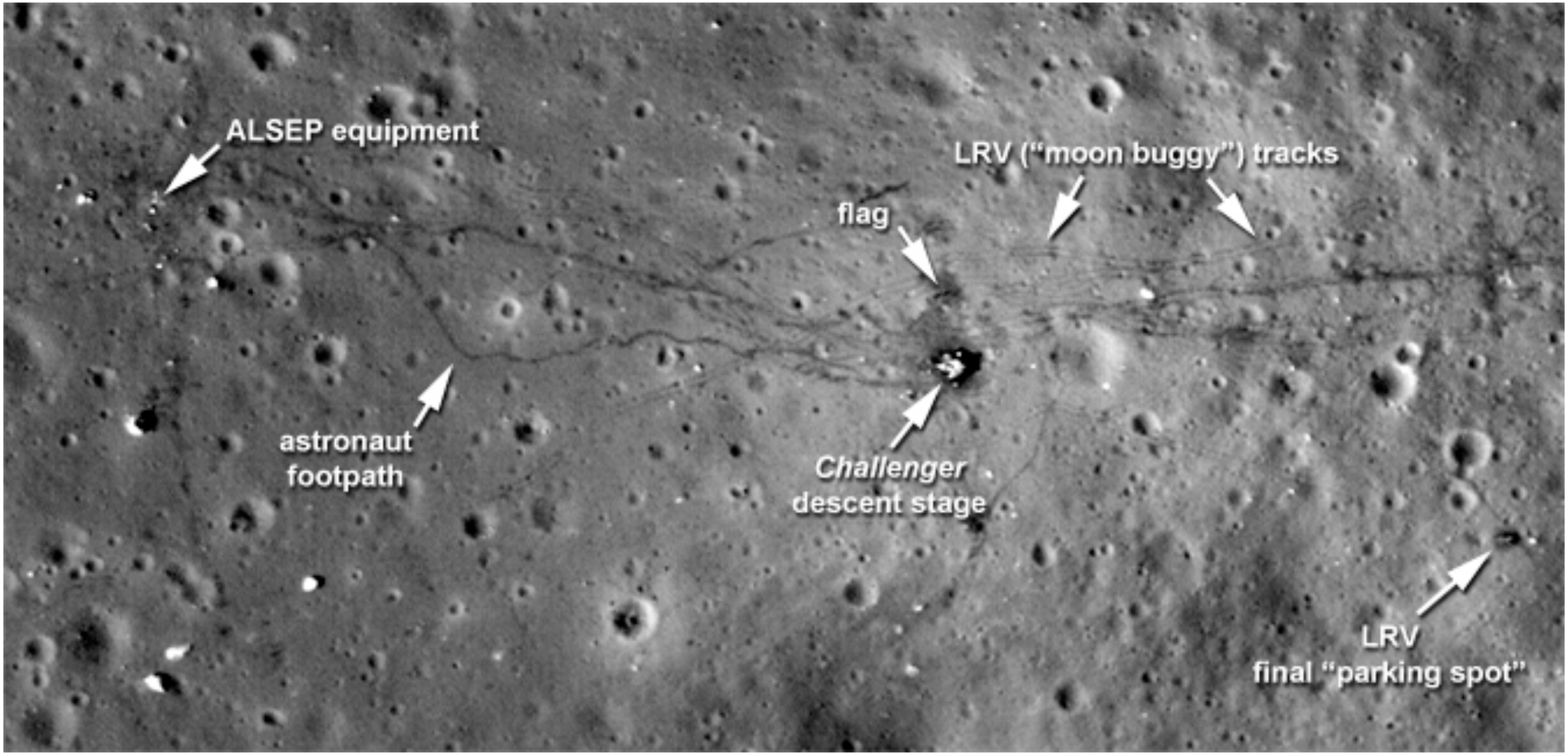
https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

Apollo 16 – Close Call



Although Apollo 16 lunar module's landing tilt was only 2.5 degrees, if it had come down less than 100 feet in any direction from that point would have placed them on a slope of between 6 and 10-degrees. Apollo 16 commander John Young commented in the mission's Technical Debrief: "I couldn't judge slope out the window worth a hoot, and that's the truth. Even down low. The ground looks flat, but I'm sure it would look flat if it had been a 6 - 8-degree slope too. I don't see any way around that."

Apollo 17 - Nominal



- No issues – but surrounded by craters

Tilt Over Abort Contingency

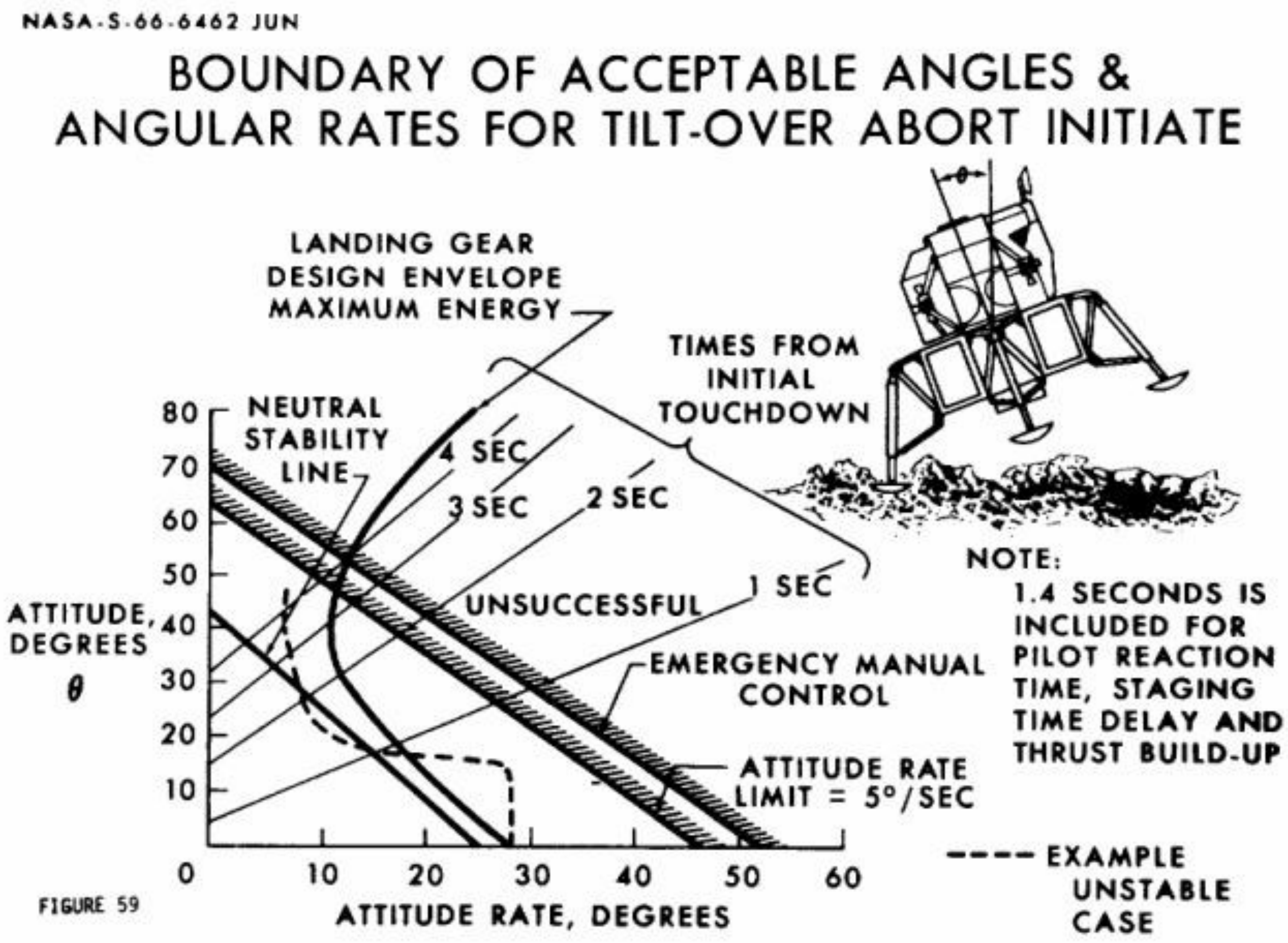


FIGURE 59

Words of Wisdom from a NASA veteran

*“To paraphrase an old bromide, those who forget the past are doomed to land like it," said **Chirold Epp** of NASA's Johnson Space Center in Houston, Project Manager for ALHAT:*

*"Having looked at the Apollo landings I have come to **two conclusions**:*

***One** -- those crews did a great job.*

***Two** -- data from several of the landings support the idea that we must give future moon landers more information to increase the probability of mission success."*

https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

NASA JSC Morpheus and Hazard Field at NASA KSC

MORPHEUS FACTS

Propellants: Methane and Liquid Oxygen

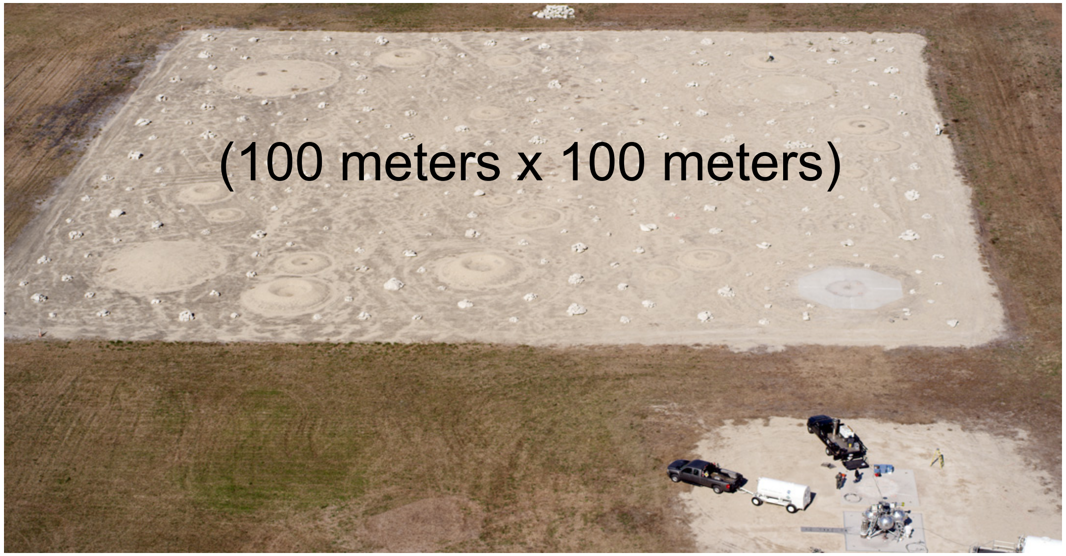
Cargo Capability: 1,100 pounds to the moon

Test Locations: NASA Johnson Space Center, Houston and NASA Kennedy Space Center, FL

Builders: NASA Morpheus Team at the Johnson Space Center, Houston and Armadillo Aerospace
https://morpheuslander.jsc.nasa.gov/about/

Morpheus Launch Video

Morpheus Landing Video



NASA "Morpheus" Flight Video

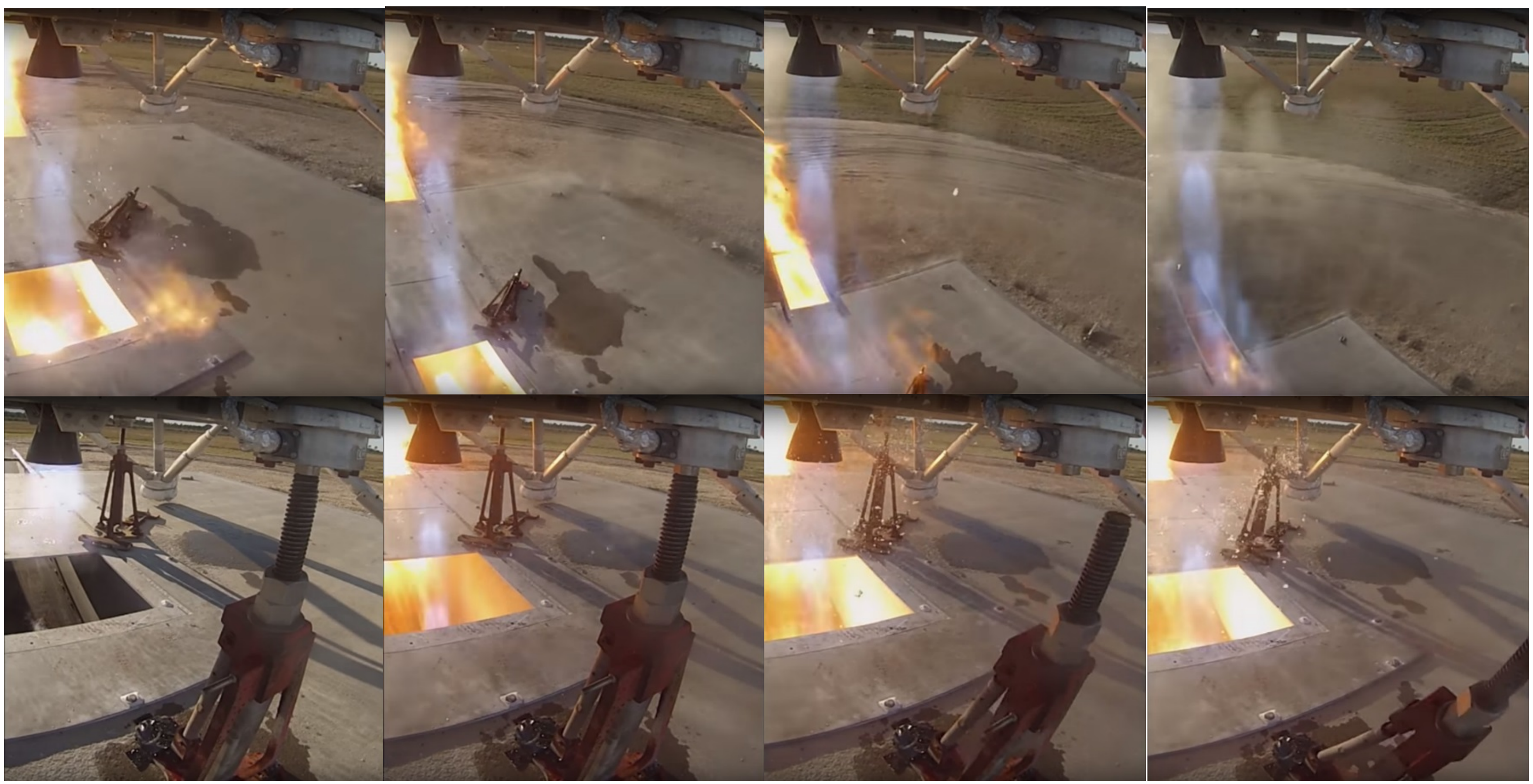
Autonomous Landing Hazard Avoidance Technology (ALHAT)

https://www.nasa.gov/mission_pages/tdm/alhat/index.html

NASA JSC Morpheus/ALHAT Free Flight 15 Testing at KSC SLF

(Images of Launch over Flame Trench)

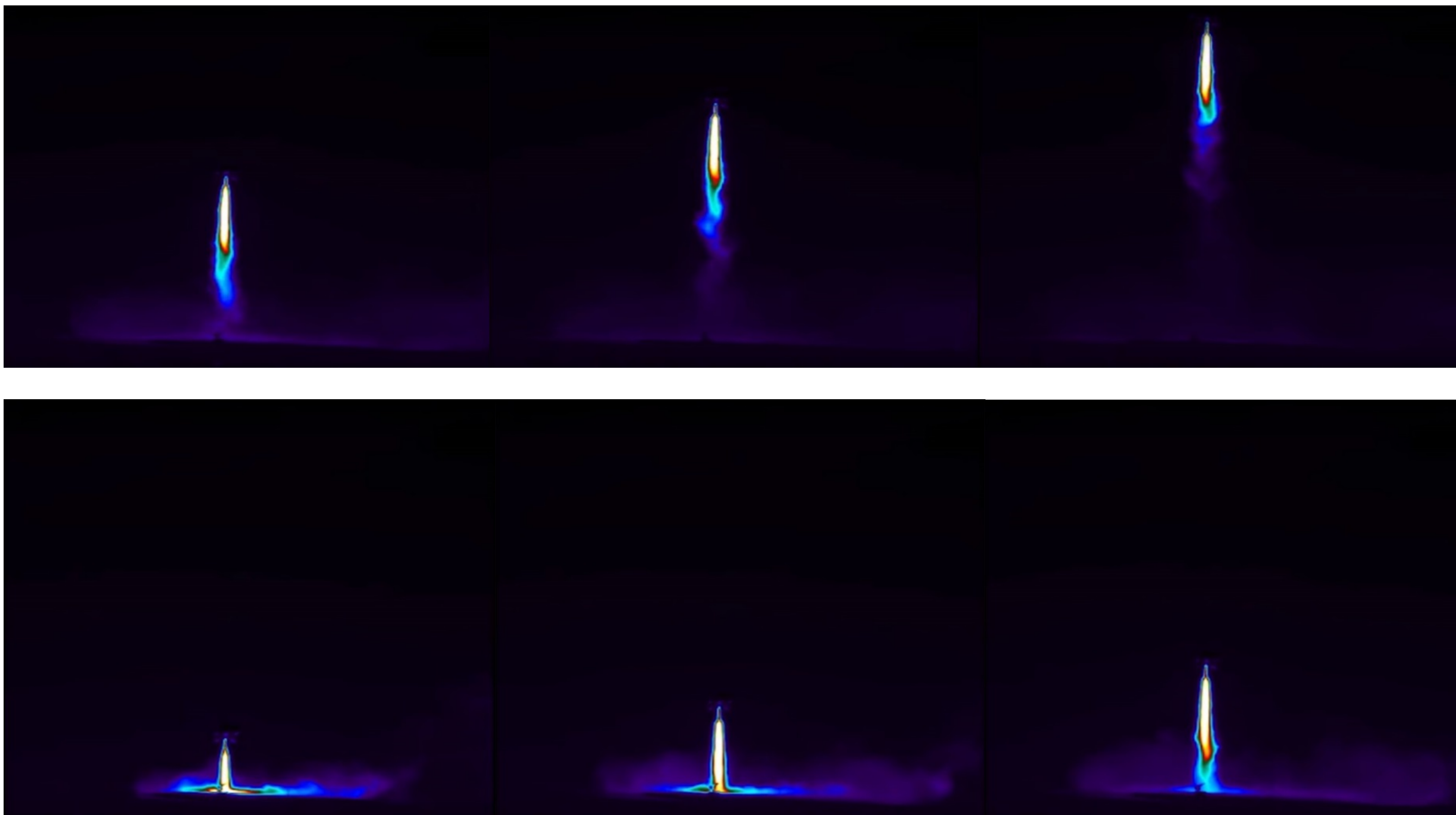
http://youtu.be/M3D9m5zhhF8 (Images: NASA)



NASA JSC Morpheus/ALHAT Free Flight 15 Testing at KSC SLF

(Infrared Camera Images of Morpheus FF15 Launch)

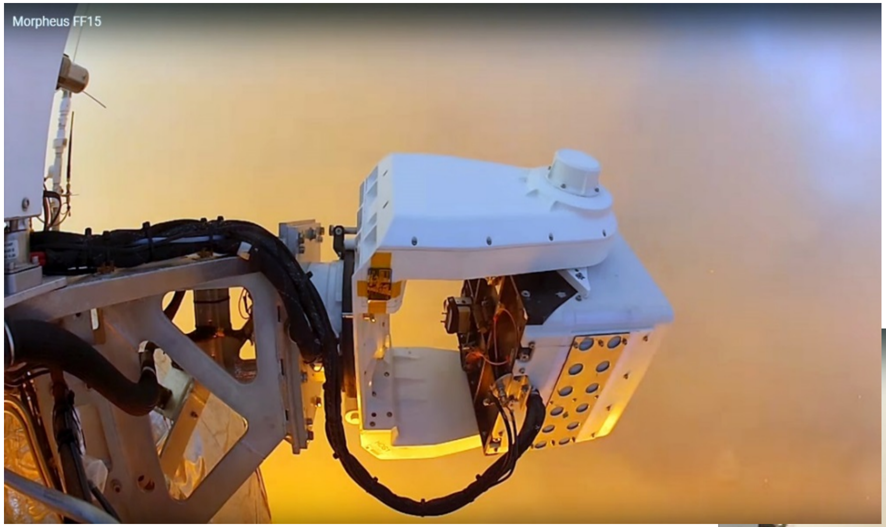
http://youtu.be/M3D9m5zhhF8 (Images: NASA)

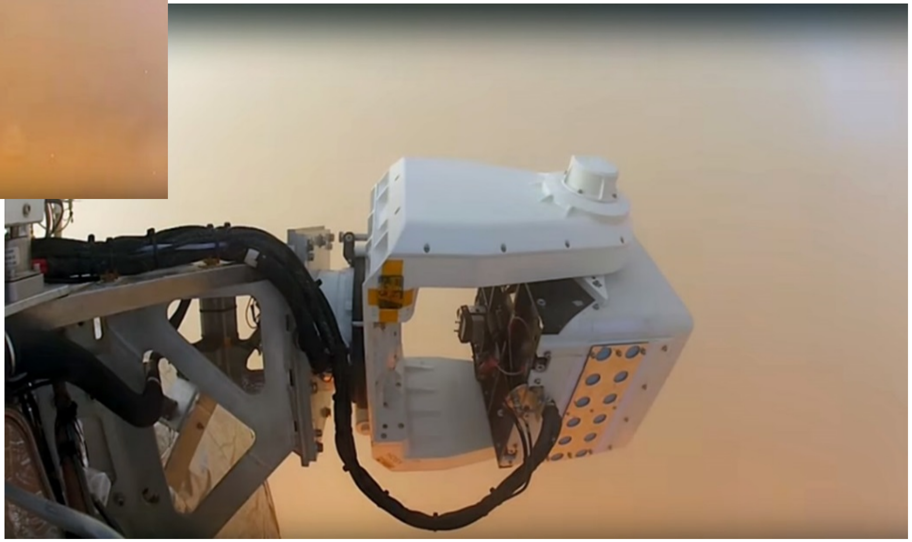


NASA JSC Morpheus/ALHAT Free Flight 15 Testing at KSC SLF

(ALHAT during Landing)

http://youtu.be/M3D9m5zhhF8 (Images: NASA)





NASA “Morpheus” Flight Video

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NASA JSC Morpheus/ALHAT Free Flight 15 Testing at KSC SLF

(Landing with Ejecta including Small Rocks)

http://youtu.be/M3D9m5zhhF8

Risk Assessment

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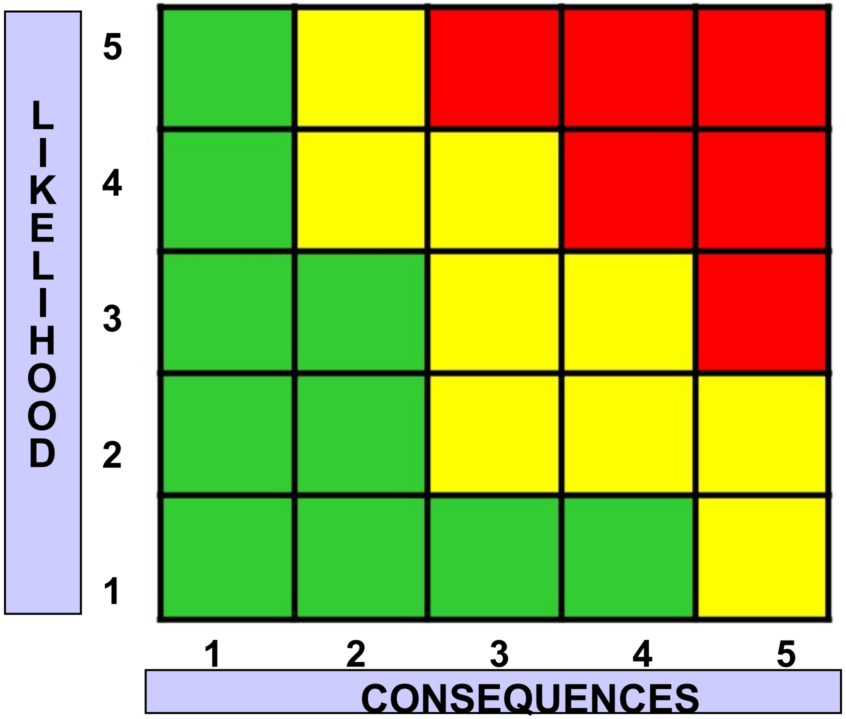
Lunar Infrastructure for Landing and Launch Risk Assessment & Mitigation

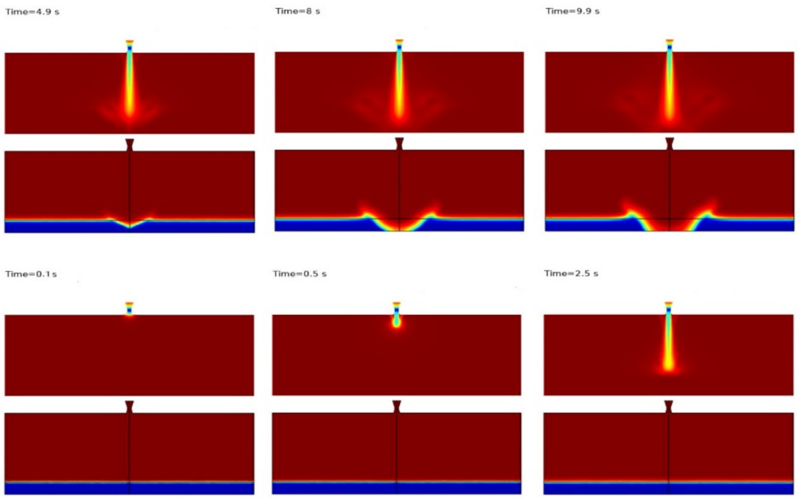


These risks need to be formally assessed

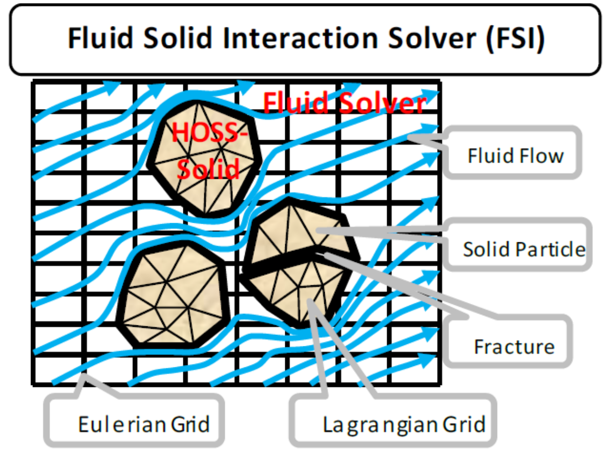
5 X 5 is per System Engineering Handbook NASA/SP-2007-6105

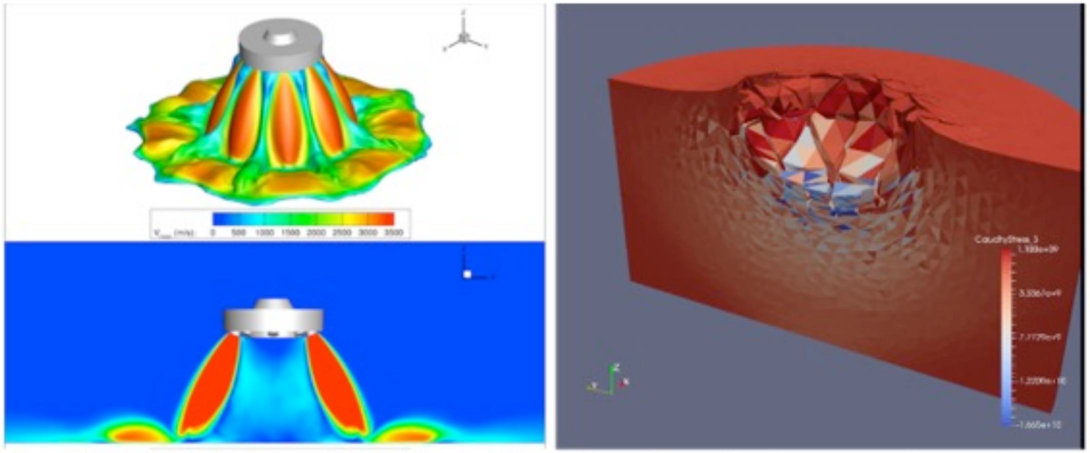
Risk ID	Risk Definition	Approach	Est. Closure Date
01	Dust Obscuration of Landing Site – sensor spoofing, loss of visuals	TBD	TBD
02	Landing slope and rock hazards exceed allowable (Apollo = 12^{o})	TBD	TBD
02	Rocket Plume Surface Interaction Effects on Lander – Dust Cloud, regolith softening	TBD	TBD
03	Rocket Plume Cratering causes Lander Instability	TBD	TBD
04	Ejecta Impacts Lander Engines and the Lander Aft End	TBD	TBD
05	Ejecta Impacts Surface Assets	TBD	TBD
06	Ejecta goes into orbit	TBD	TBD
07	Separation distance of Lander from Lunar Habitat	TBD	TBD
08	Lunar base flyover issues – flight corridors	TBD	TBD
09	Rocket engine ignition overpressure pulse causes damage to Lander or surface during launch	TBD	TBD

CFD* Surface Plume Interaction Modeling



Example of CFD Modeling of Rocket Plume Impingement on Surface Regolith for a Human Lander (NASA KSC)





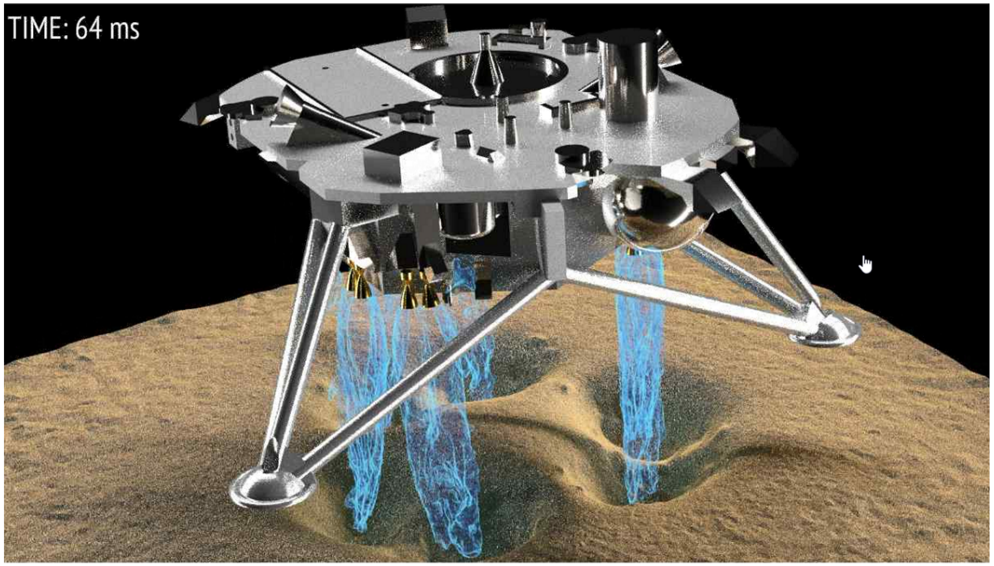
(Left) CFD Simulation of complex multi-engine plume impingement interaction for human class Mars lander concept. (Right) Structural simulation demonstrating extreme fracture and fragmentation incorporating material plasticity processes. Crater bulging and extreme deformation can be seen at the bottom of crater

PI: Ranjan Mehta , CFD Research Corporation

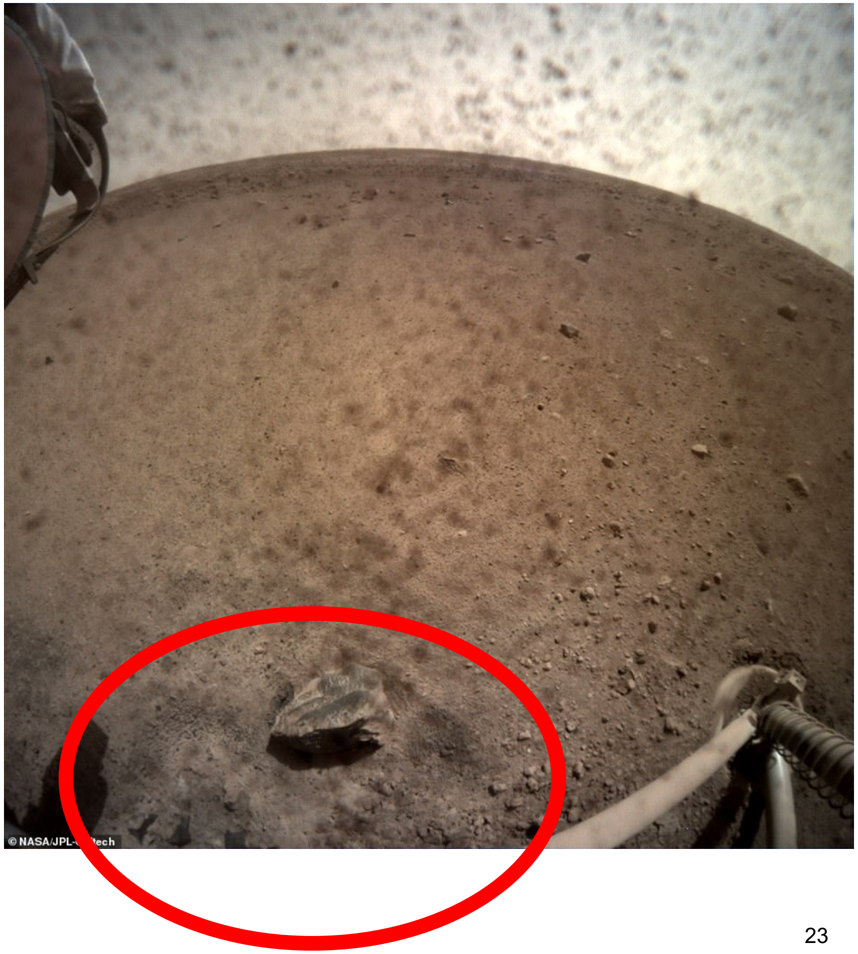
* Computational Fluid Dynamics

Simulation Tools are improving

- CFD Research Corporation NASA SBIR: Gas-Granular Flow Solver
- Mars Insight Mission: Coupled Gas-Granular Erosion

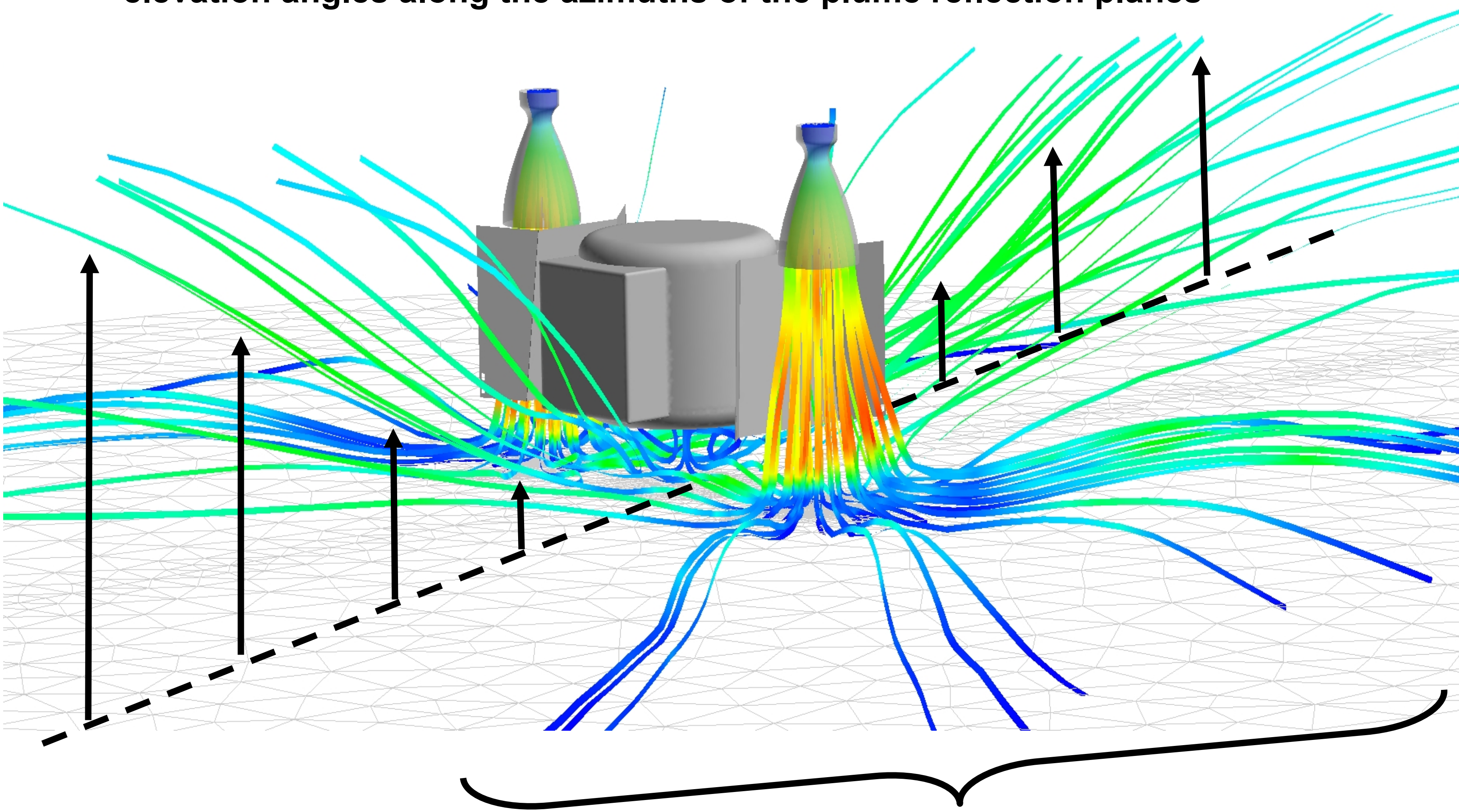


Credit: Manuel Gale & Peter Liever, CFD Research Corp.



Additional Issues: Plume Reflection Planes

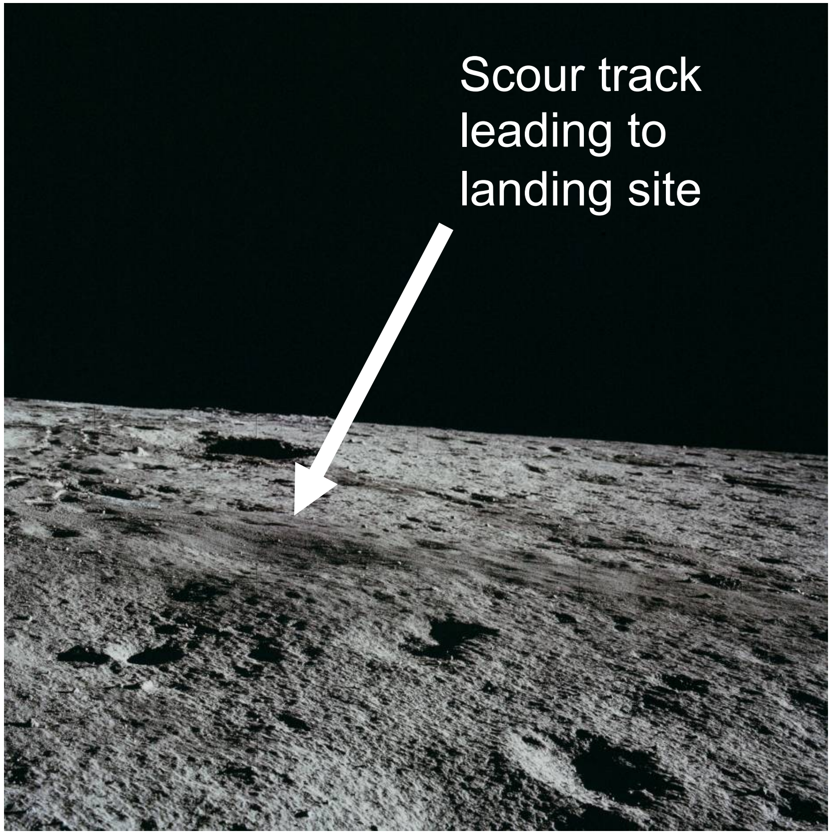
- Plume interactions for multi-engine landers may eject soil at higher elevation angles along the azimuths of the plume reflection planes

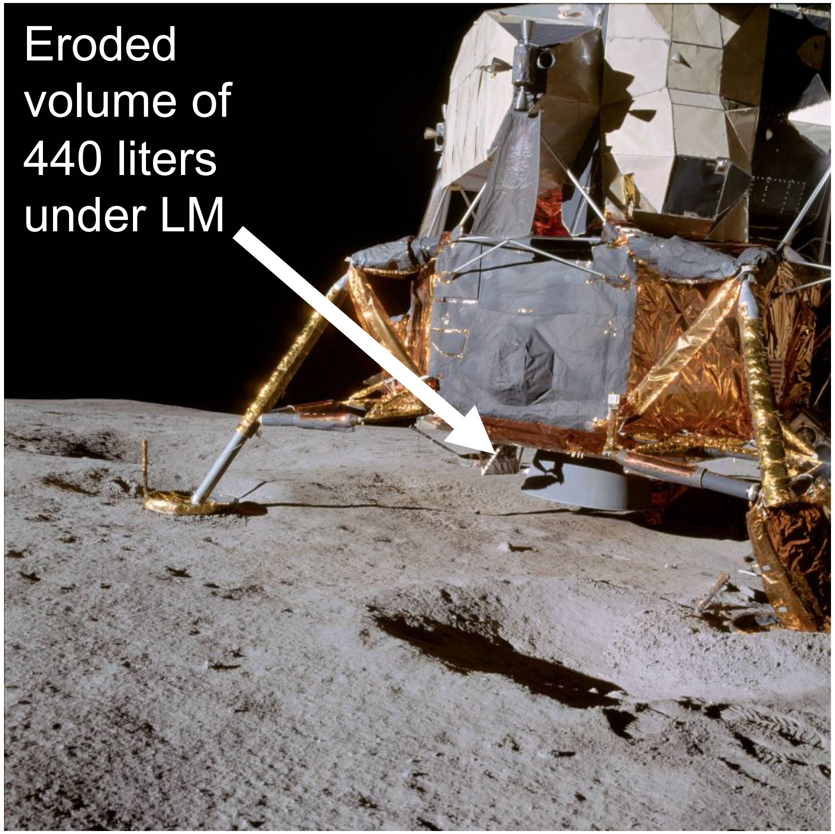


Source: Bruce Vu, NASA KSC, Lunar Lander Studies 2006

Other Issues: Surface Modification Under Bells

- **Local terrain modification occurred routinely under the LM just prior to touchdown [1]**
- **This alters the gas flow and may have created a briefly higher angle of ejection**
  - This “soil blowout” event is visible but not scalable in the videos

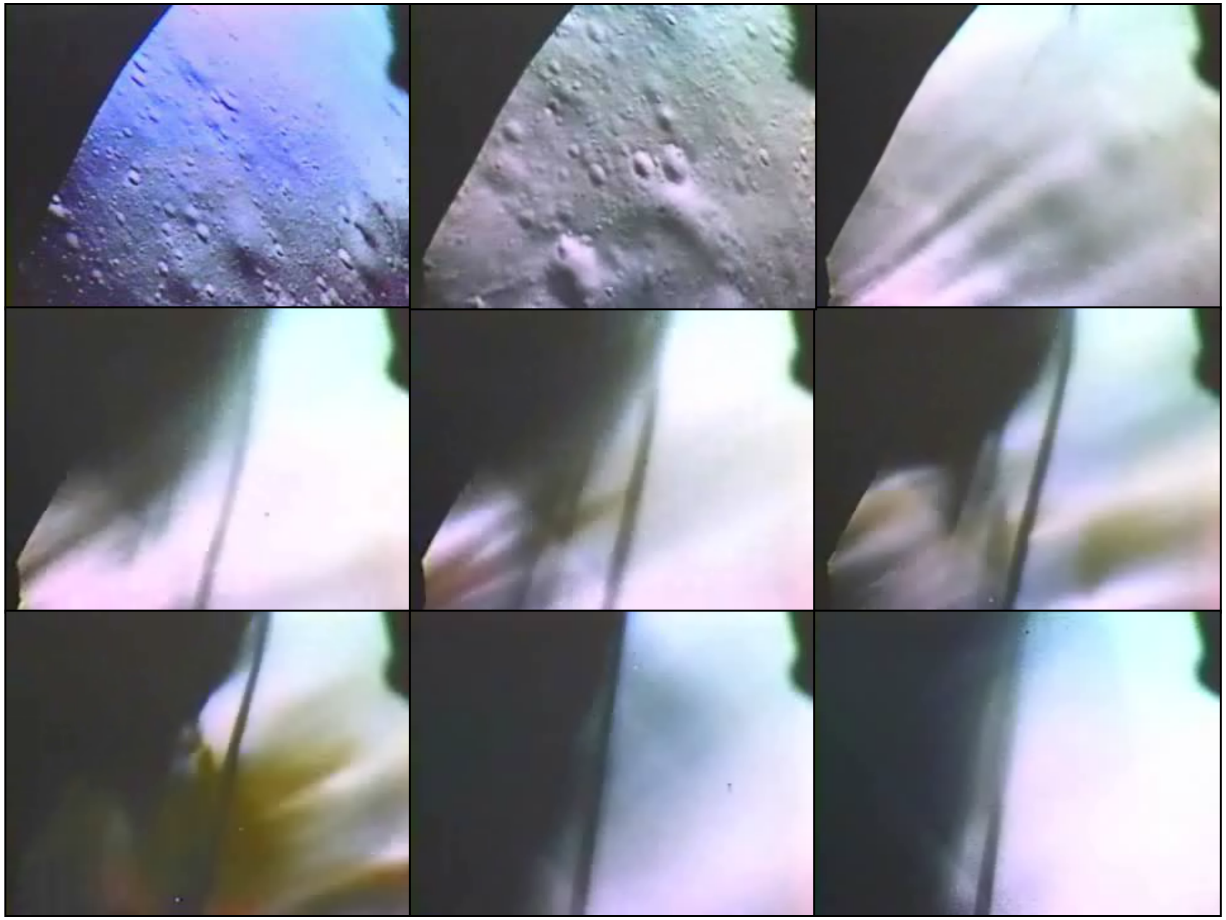




Source [1]: Katzan, C. M., & Edwards, J. L. (1991). Lunar dust transport and potential interactions with power system components., p. 9.

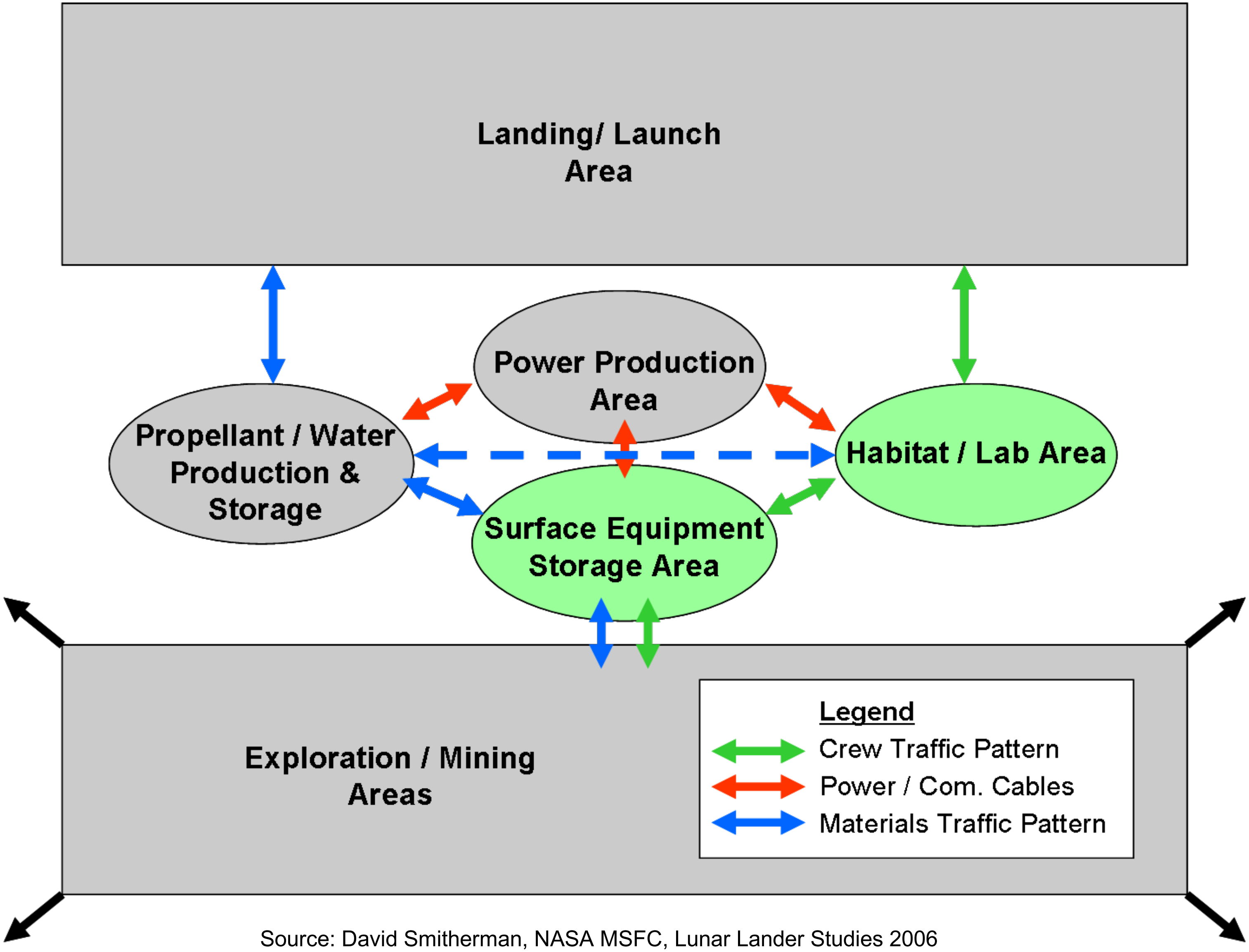
Surface Modification Under Bells, continued

- "Soil blowout" near touchdown is common event in Apollo landings
- Probably due to vastly increased erosion rate when engines are near surface
- Probably related to localized scour holes under nozzles after landing



Source: Apollo 15 landing video, converted by Gary Neff

Lunar Base Functional Concept



Source: David Smitherman, NASA MSFC, Lunar Lander Studies 2006

Quantity-Distance (QD) Explosion Setbacks

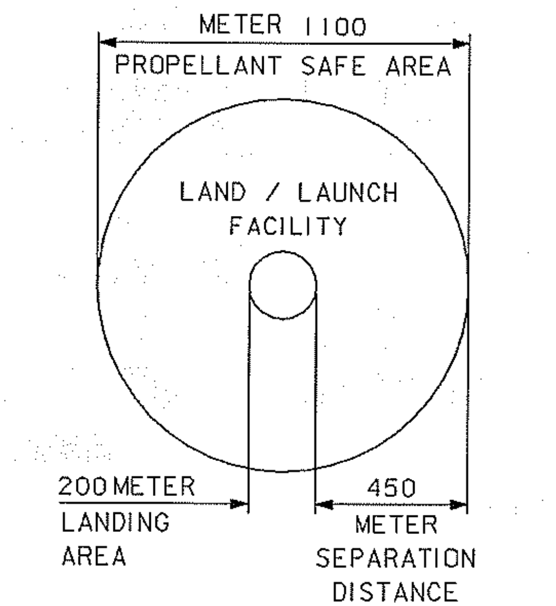


Figure 11 - Launch Landing Area

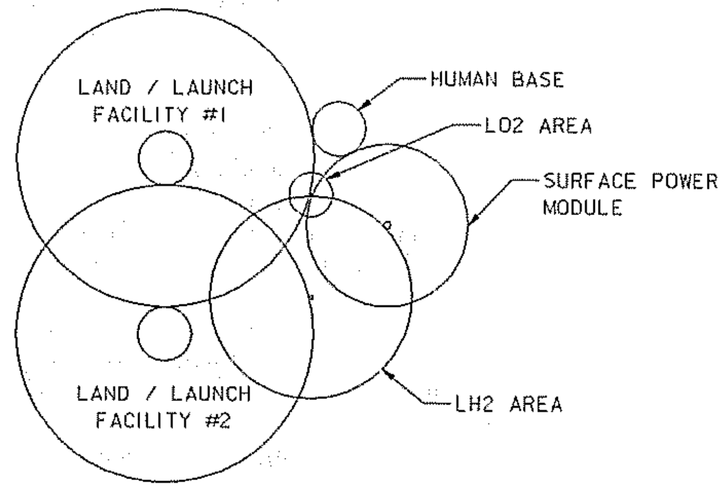


Figure 12 - Lunar Base Surface Use Plan

Source: Rob Mueller, Swamp Works, NASA, KSC

DOT & DOD explosives standards and tables exist for Earth use <u>but not for the Moon</u>

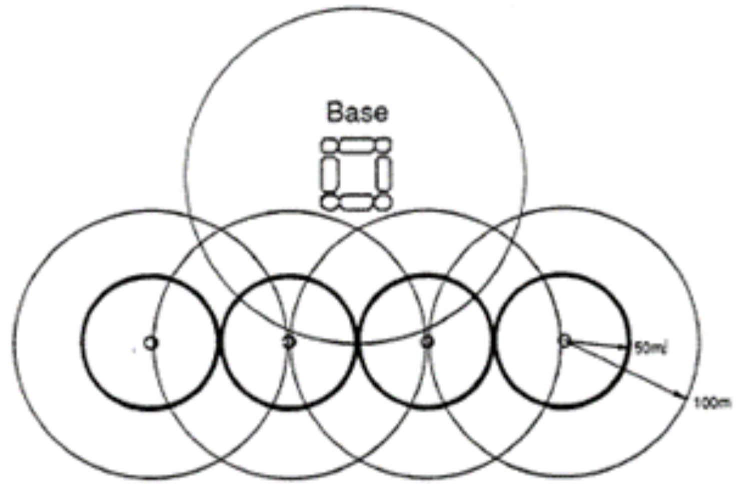
The image on the right shows the safe distances between pieces of infrastructure based on QD Explosive setbacks, and shows that there is planning involved in positioning everything – in contrast to the idyllic artist renderings.

1988 Eagle Engineering Studies – NASA SEI

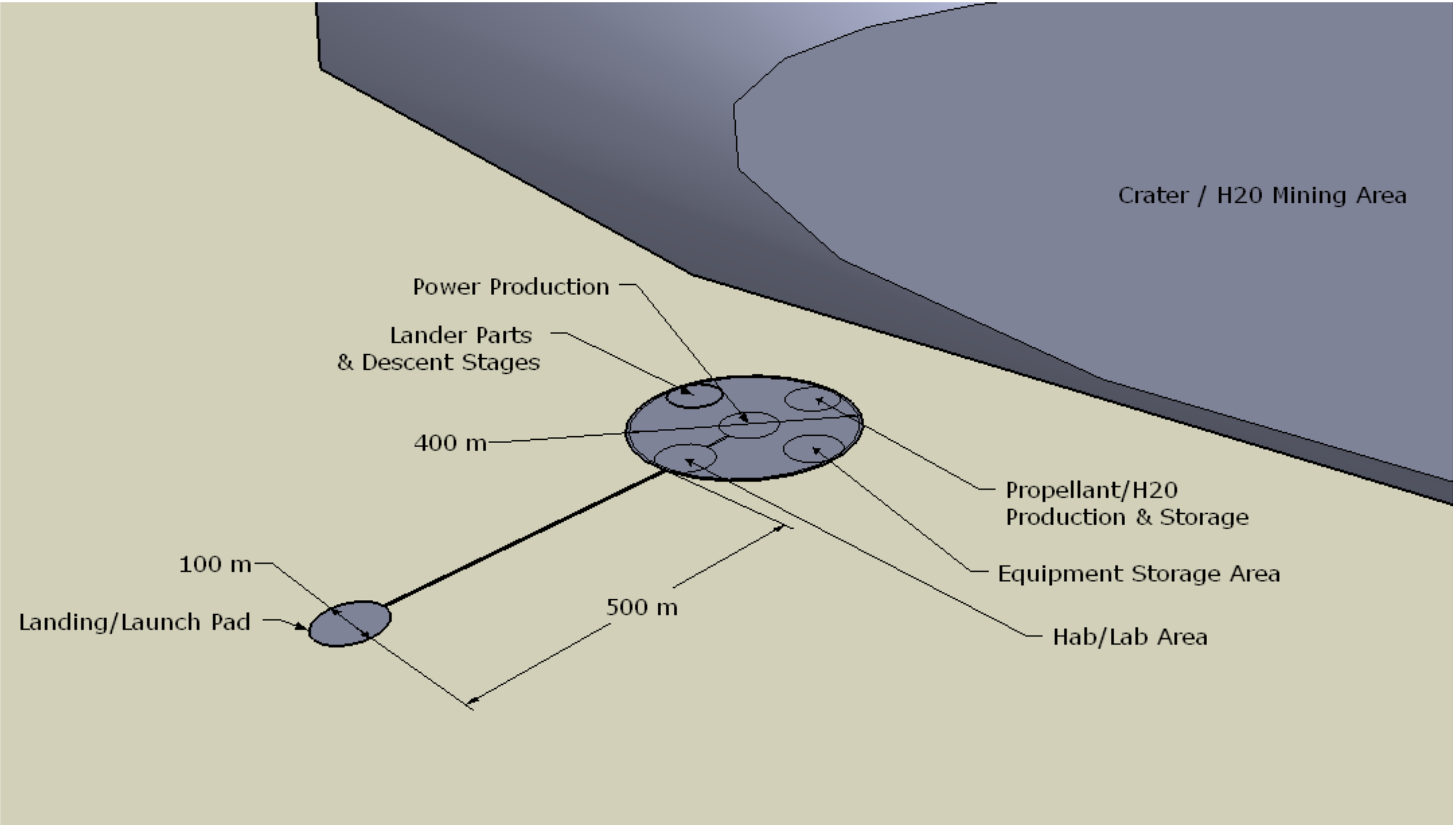
Lunar Base
Launch and Landing Facility
Conceptual Design

NASA Contract Number NAS9-17878
EEI Report 88-178

EAGLE



Lunar Base Master Planning Example

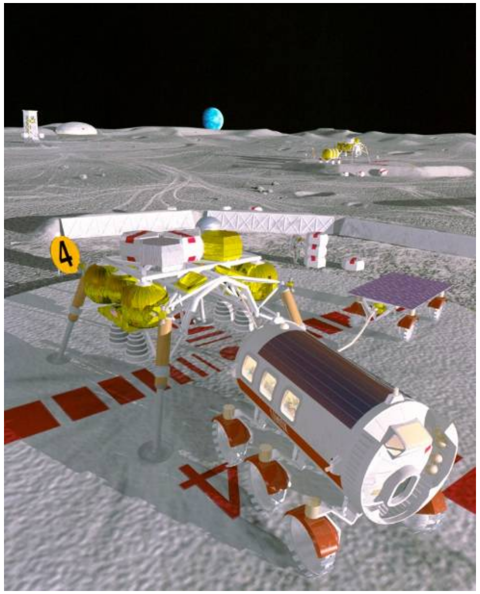


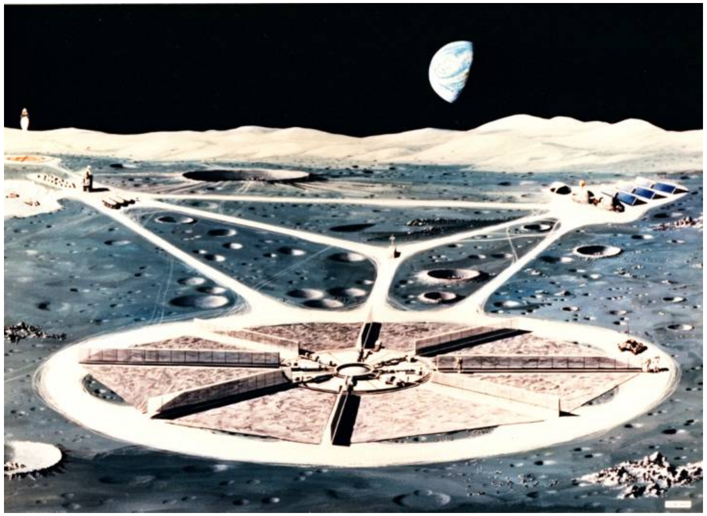
Source: Rob Mueller, Swamp Works, NASA, KSC

Surface Preparation and Construction of a Landing and Launch Area

TASK		Mass of Regolith (Kg)	Regolith Excavation Rate (Kg/Hour)
Surface leveling / Roads	2.5 km	562,500	400
Berm-building	4m high x 100 m long	2,400,000	600
Trenching	3 m deep x 12 m long	54,000	200
Regolith radiation & thermal shielding	3m thick x 12 m long	720,000	600
Hole digging	4m deep x 1m diameter	1,178	300
Launch/Landing Pads	100 m diameter	353,250	400

Source: Rob Mueller, Swamp Works, NASA, KSC





Landing & Launch Pad Concept

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- **Landing & Launch Pad is nominally 50 m diameter for precision landing surrounded on the base side by blast mitigation regolith berms**
- **Landing pad could be smaller if beacons and other Navigational Aids were deployed**
- **Based on Apollo Core samples – it is possible to remove the top 30 cm of regolith or provide another method of mitigating dust and stabilizing the regolith. Disturbed regolith could be re-set with vibratory compaction.**
- **Some method of regolith stabilization against the rocket engine surface plume interaction is needed for repeated landing and launch operations**
- **Pad inspection and maintenance need to be considered for repeated L&L operations and avoid risk of creating larger mass debris in ejecta**
- **Roads to and from the L&L Pad are recommended to increase duty cycle of mobility platforms and to simplify deployment of mobile assets from the landers**

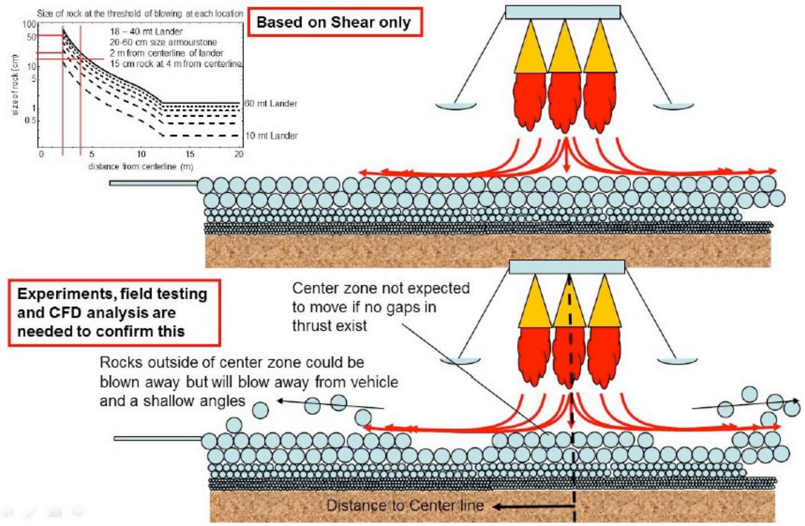
Source: Rob Mueller, Swamp Works NASA, KSC

Surface Modification Under Engine Bells

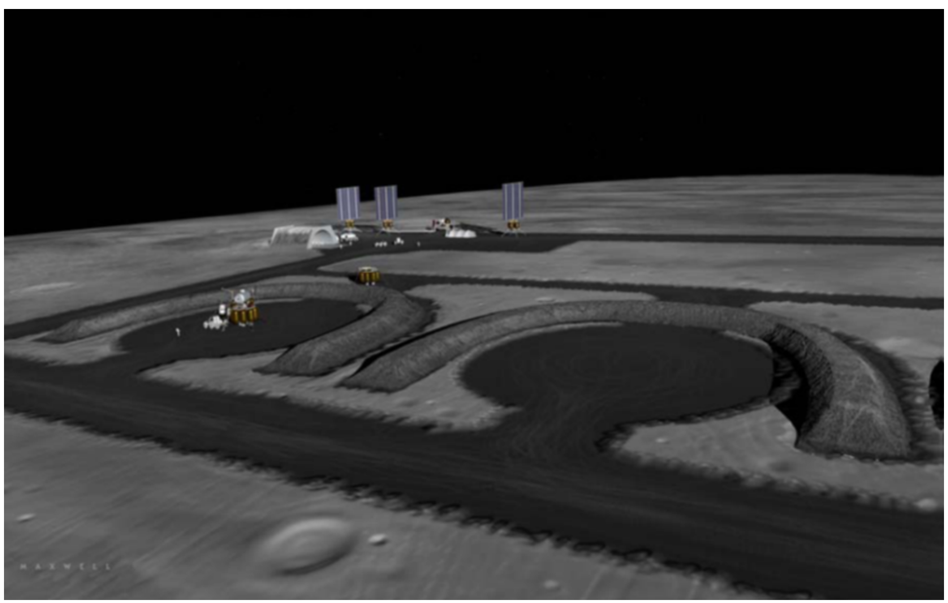
- **Lunar soil is "internally erodible": Gas injection under engines is expected to loosen and crater the soil**
  - Recent experiments indicate that this is the primary cratering mechanism under an engine nozzle [2]
- **This will eject soil at a higher angle, possibly over the lip of a berm**
- **May be prevented by stabilizing the soil via one or more of the following:**
  - Remove the looser surface material
    - Done "for free" when the surface is leveled and scrapings used to build a berm
    - Need to analyze if this is a complete solution
  - Lay down a gravel base
    - Leftovers from ISRU processes
  - Sinter via microwaves or solar concentration
  - Use Pavers manufactured "in-situ" of sintered regolith
  - Add palliatives to the soil
    - U.S. military's technique at desert landing sites
  - Lay down and anchor a fabric mat brought from Earth

Source [1]: David A. Carrier, "Particle Size Distribution of Lunar Soil," *J. Geotech. and Geoenv. Eng.* **129**, 956-9 (2003).
Source [2]: Metzger, *et al.*, "Jet-induced cratering of a granular surface with application to lunar spaceports," submitted to *J. Aerospace Eng* (2006).

Some Recent Landing Pad Concepts



Paul Van Susante – Michigan Technical U / NASA



Artist: Maxwell for NASA

ACME sintered basalt paver pad: NASA / PISCES

Observations

- **Larger Human Crew Class Landers will have more plume effects issues than Apollo due to higher engine thrust**
- **Risk mitigation concept for a general solution:**
  - Level the landing surface
  - Stabilize soil at landing site
    - Perform trade study for various methods
  - Build a berm between the landing site and other hardware
    - requires significant excavation time
    - Based on the Apollo ejection angle of 3 degrees, we may limit the berm height to 2 meters by tightening the landing accuracy to 35 meters
- **Point the multi-engine plume reflection planes away from the surrounding hardware during final descent**
- **Develop better simulation tools to validate these recommendations**
  - Development underway via NASA PSI team and other means
  - Experimental work required to calibrate tools
- **Develop concepts (with analysis) for Landing & Launch Pad**

- **Open up the ideation space and awareness via discussion at the Space Resources Roundtable - 2019**