Guidelines on Lunar Infrastructure Engineering, Design, Analysis and Construction

By

Ramesh B. Malla, Ph.D., F. ASCE, F. EMI, A.F. AIAA

Chair, ASCE ASD Space Engineering and Construction Technical Committee

University of Connecticut, Storrs, CT

Presentation to

NASA/Lunar Surface Innovation Consortium (LSIC)

- Excavation & Construction Monthly Meeting

(Virtual)

February 22, 2023

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*19th Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction and Operations in Challenging Environments-2024. [First Conference "**Space 88** – Engineering and Construction in Space: Name changed to "**Earth & Space 2004**" in 2004 to broaden the Scope)]*

- **Conference Proceedings:** with Peer reviewed full-length papers to be published by ASCE Publications
- **Short Course** – the First day of the Conference,

Journal of Aerospace Engineering (Established 1988)–The Journal of Aerospace Engineering promotes the implementation and development of space and aerospace technologies and their transfer to other civil engineering applications

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Technical Committee on Space Engineering and Construction

(est. 1988)

Purpose:

- To review, evaluate, promote. and report on advancements in engineering, construction, and operations in space frontier and extraterrestrial planetary bodies, and on challenging/extreme environments on Earth.
- To encourage dual technology development and promote transfer of technologies and know-how in various civil engineering disciplines between terrestrial and extraterrestrial applications and development, and between civil and other engineering and science areas.
- To provide a common platform to exchange knowledge and technology advancements. This ~~is~~ will be accomplished through workshops, conferences, forums, educational initiatives, and publications.

(Date revised: 14 August 2019)

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Space Engineering and Construction (SEC)

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Ramesh B. Malla, Ph.D., F. ASCE, F. EMI, A.F. AIAA
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ASCE ASD Space Engineering and Construction Technical Committee (SEC TC)
Presentation to
NASA – Lunar Surface Innovation Consortium (LSIC)/ JHU- Applied Physics Lab

February 22, 2023

ASCE ASD SEC TC
Guidelines on Lunar Infrastructure Engineering, Design, Analysis and Construction

Objective/Scope

- Develop a **comprehensive set of guidelines** for engineering design, analysis and construction of various essential infrastructure on the moon for *short, medium and long-term* missions and operations.

- The guidelines will emphasize and be developed for practical engineering use.

- Planned to deal with the following key topical areas of significant practical importance:
  - *Construction and Materials*
  - *Design Loads*
  - *Environmental Consideration and Effects*
  - *Geotechnical and Foundation Engineering*
  - *Structural Design, Analysis and Architecture*

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The Benefits of Guidelines

- Ensure structures stability by identifying and mitigating potential hazards such as seismic activities, extreme temperature fluctuations.
- Ensure the structures are not only durable but also environmentally friendly. Sustainable design principles should focus on minimizing the use of resources and maximizing energy efficiency.
- Providing safe and reliable habitats for astronauts, as well as protecting against the harsh lunar environment. This includes considerations for life support systems, radiation shielding, and thermal insulation.
- Encourage collaboration among stakeholders, including architects, engineers, and scientists, to ensure that the structures are designed with the latest technology.
- Enable structures to be easily modified or expanded as needed, without requiring extensive rework or redesign.
- The Infrastructure engineering design and construction guidelines for moon-based structures should be cost-effective, taking into account the unique challenges and constraints of working on the moon.

(I) Construction & Materials

Objective/Scope:

- **Building on top of state-of-the-art advancements in terrestrial and extra-terrestrial construction, develop guidelines for construction in the lunar environment that includes the following information for various types of lunar infrastructure**

➢ Design Objectives
-Infrastructure Type, Site Conditions, Protective Needs, Technical Needs

➢ Material Resources
-Payload from Earth, In situ Resource Extraction and Utilization, Hybrid Utilization

➢ Construction Techniques and Methods
-In-space Robotic Construction/Manufacturing, Assembled Payloads from Earth

➢ Mode of Operation
-On-Site, Station Based and Earth Based Human Operated Equipment and Telerobotics, Autonomous Robotics

➢ Quality Control and Safety Assessment
-Earth Shop Test Plan, Pre-Launch Test Plan, Post Landing Inspection Plan, Installation Test Plan, NDT Structural and Thermal Safety Testing, Sub-system Test Plan, System Testing and Commissioning

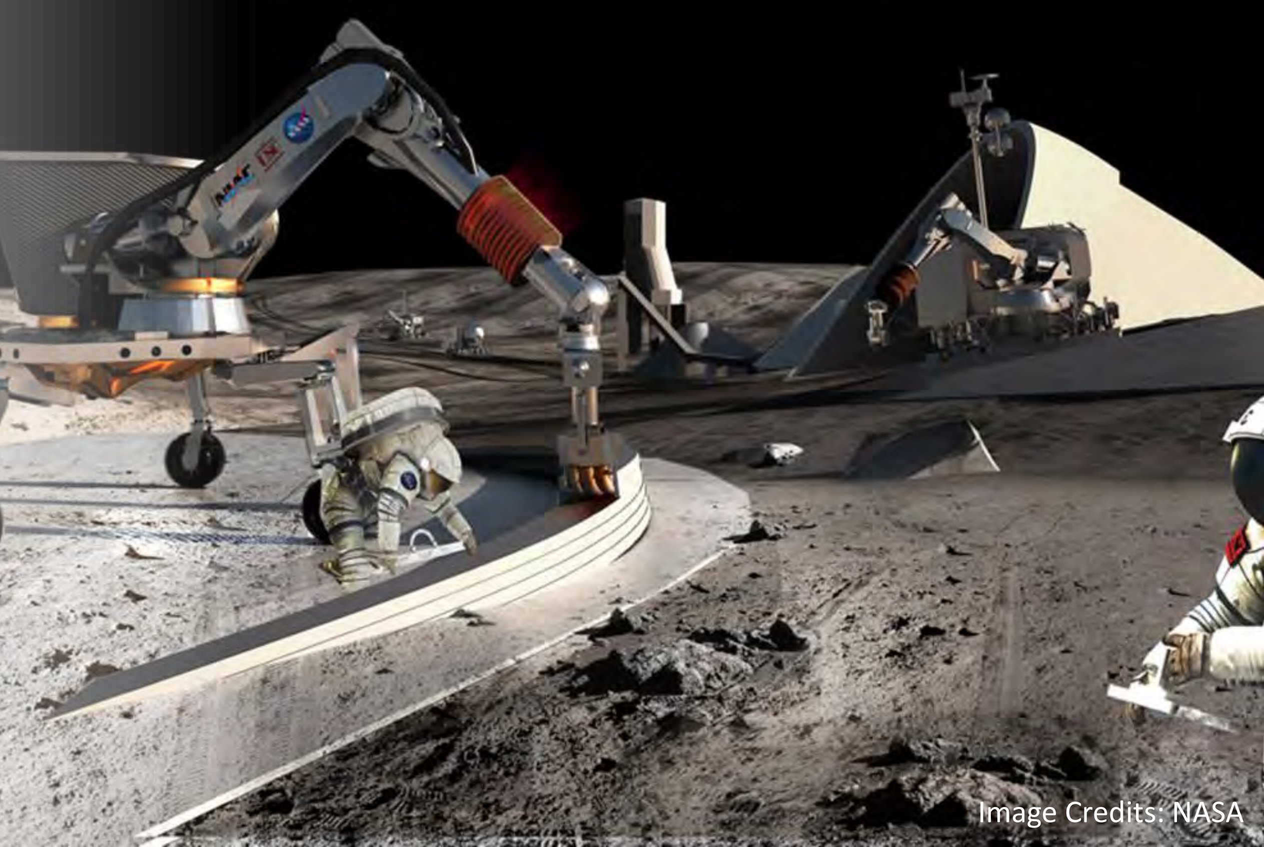

Image Credits: NASA

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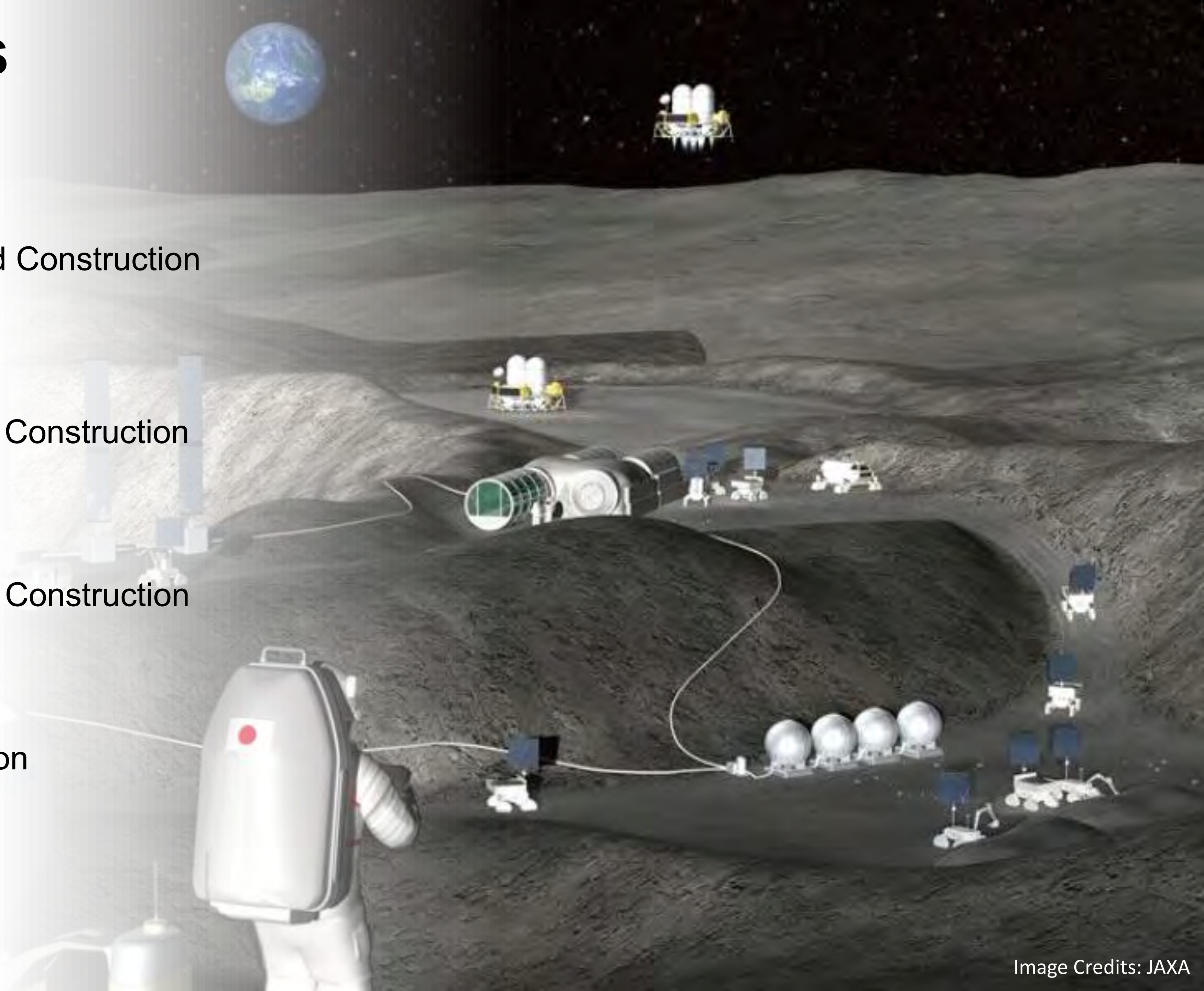


Image Credits: JAXA

Lunar Launch/Landing Pad Construction

Sample

- **Design Objectives**
  - -Need for levelled surface
  - -Need for hardened/compacted surface
  - -Need to withstand stress/heat caused by rocket plume loading and mitigate debris scattering
  - -Need to withstand degradation over time due to repetitive launches/landing
  - -Power lines for safety lights and other electronic sensors if any
- **Material Resources**
  - -Lunar Regolith
- **Construction Techniques and Methods**
  - -Compaction/Hardening of lunar regolith using methods like sintering
  - -Additive deposition of cementitious regolith material using ISRU techniques
- **Mode of Operation**
  - -Robotic arm on mobile rover with targeted sintering end effector
  - -Robotic arm on mobile rover with nozzle to deposit cementitious regolith mix
- **Quality Control and Safety Assessment**
  - -Surface Levelling testing
  - -Surface Compaction testing
  - -Surface thermal and structural loading testing
  - -Surface degradation due to cosmic radiation testing

Image Credits: University of Texas, San Antonio

Solar Power Tower Construction

Sample

- **Design Objectives**
  -Need for tall truss based structures that can hold solar panels
  -Need for integration of power distribution systems

- **Material Resources**
  -Assembled payload from Earth
  -In-space manufacturing of thin film solar panels

- **Construction Techniques and Methods**
  -Robotic leveling of surface
  -Anchoring of foundation of tall solar towers to ground
  -Assembly/Erection of truss using automated robotic mechanisms
  -Unfolding of folded solar panels using automated mechanisms

- **Mode of Operation**
  -Rovers to deploy preassembled solar towers in selected locations
  -Automation to level or anchor truss based solar towers to ground

- **Quality Control and Safety Assessment**
  -Truss Structural Testing
  -Photovoltaic Performance Testing before and after unfolding
  -Power Distribution Cable Efficiency Testing

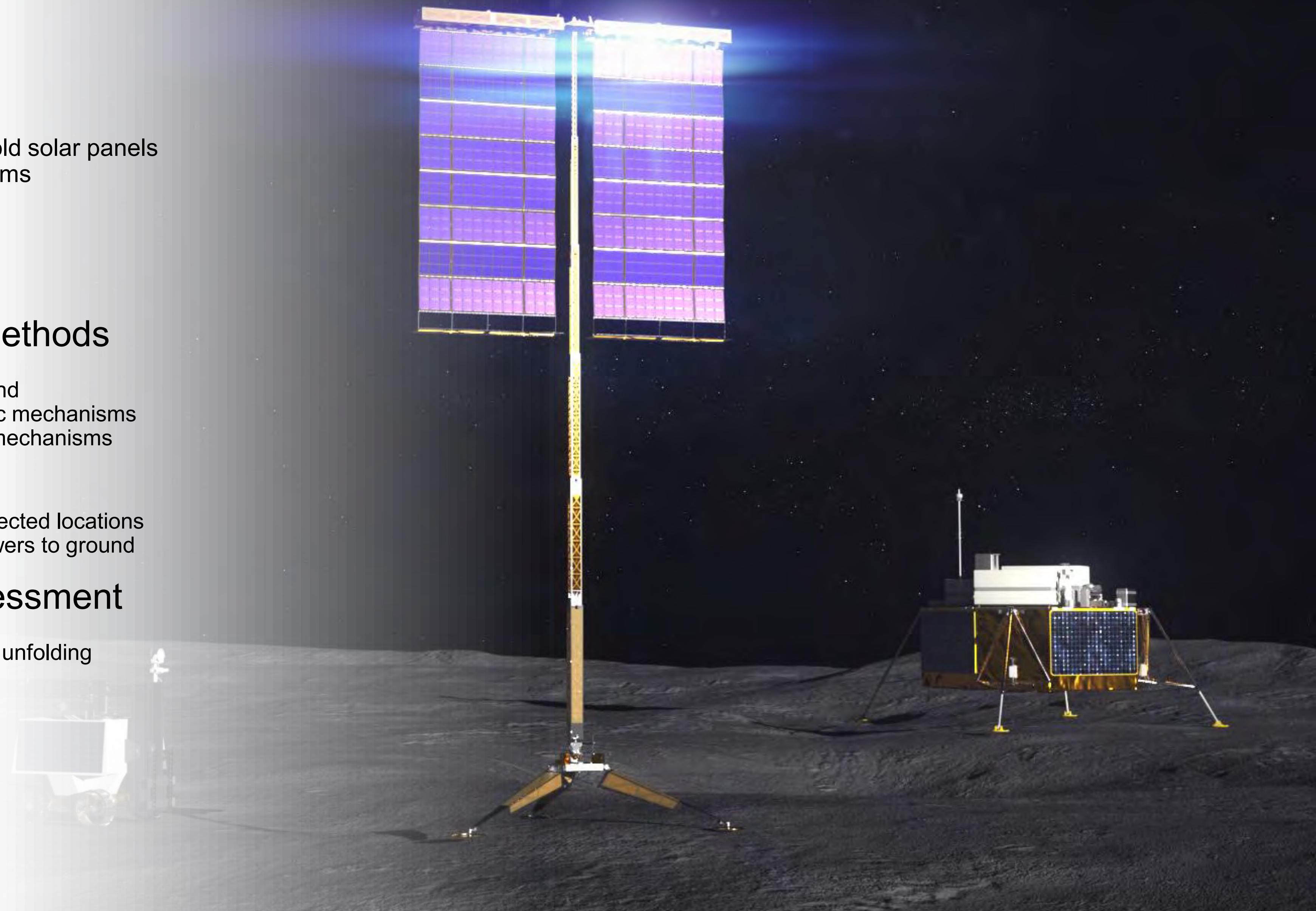


Image Credits: NASA

Unpressurized Storage Facility C

Sample Topic

- **Design Objectives**
  -Need for unpressurized structures with clear access for large equipment and machinery
  -Need for debris and radiation protection for sensitive electric storage if any
- **Material Resources**
  -Lunar Regolith
- **Construction Techniques and Methods**
  -Additive deposition of cementitious regolith material using ISRU techniques
- **Mode of Operation**
  -Robotic arm on mobile rover with nozzle to deposit cementitious regolith mix
- **Quality Control and Safety Assessment**
  -Compressive and Lateral load Testing

Image Credits: NASA

Pressurized Habitat Construction

Sample Version of Chapter

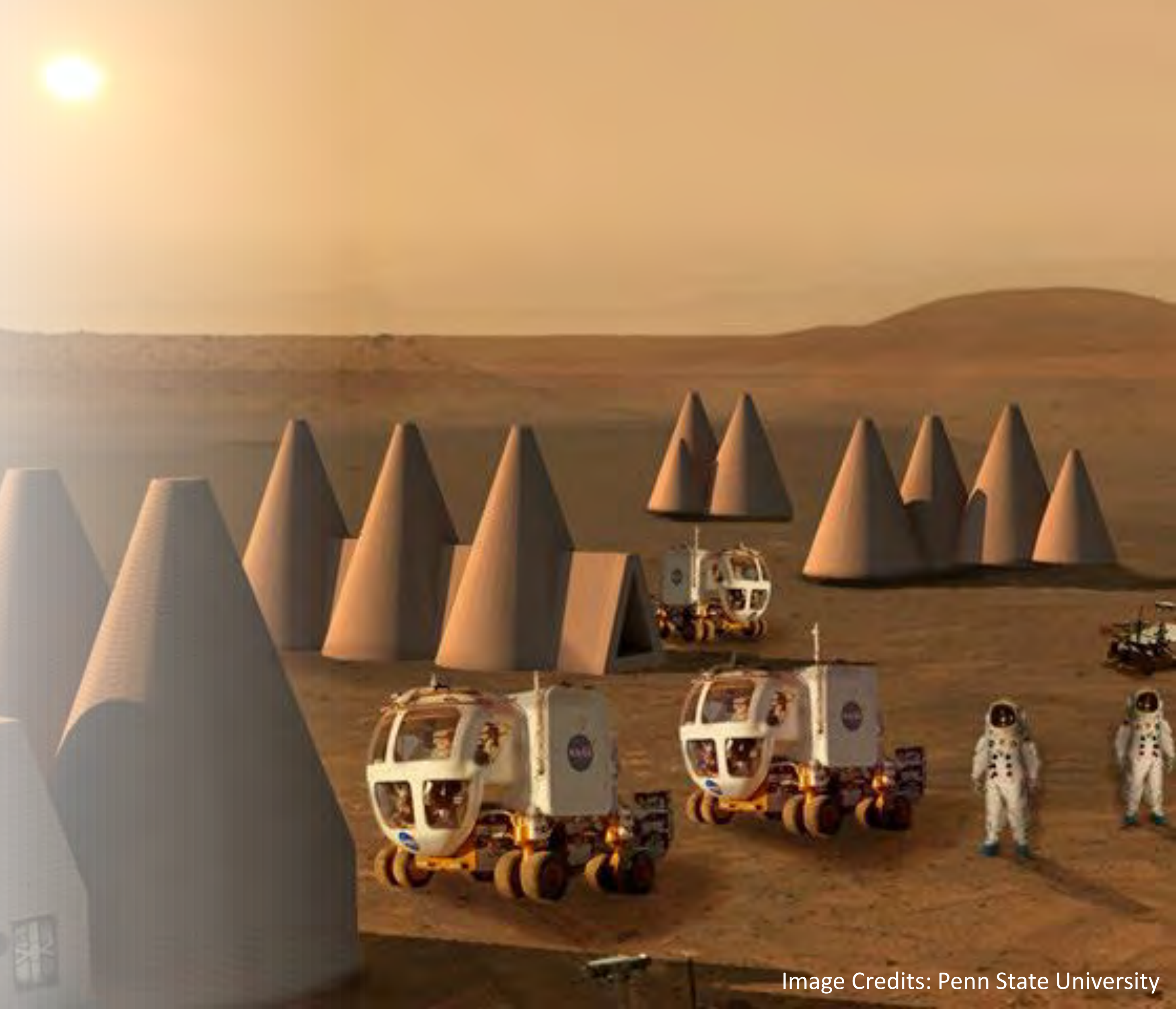
- **Design Objectives**
  - Need for structural systems that can counteract lateral loads due to reduced outside atmospheric pressure and reduced gravity
  - Need for MEP, ECLSS, power generation, storage and distribution and food production systems that support safe human habitation
  - Need for access docks for space suit and rover docking

- **Material Resources**
  - Lunar Regolith
  - In-space manufacturing of building sub-components such as power distribution wires, solar panels etc.

- **Construction Techniques and Methods**
  - Compaction/Hardening of lunar regolith using methods like sintering
  - Additive deposition of cementitious regolith material using ISRU techniques
  - Robotic outfitting of buildings with various systems

- **Mode of Operation**
  - Robotic arm on mobile rover with targeted sintering end effector
  - Robotic arm on mobile rover with nozzle to deposit cementitious regolith mix
  - Robots for outfitting

- **Quality Control and Safety Assessment**
  - Structural Testing
  - Thermal and Infiltration Testing
  - Safety Systems Testing



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(II) Lunar Structural Design Loads

Objective/ Scope:

- To develop a preliminary set of tangible structural load criteria for designing Lunar buildings and infrastructure,
- Load criteria will be based on accepted terrestrial based design standards and practices,
- Modifications will account for the Lunar environment
- Criteria can be used for future development of Lunar design standards and building codes.

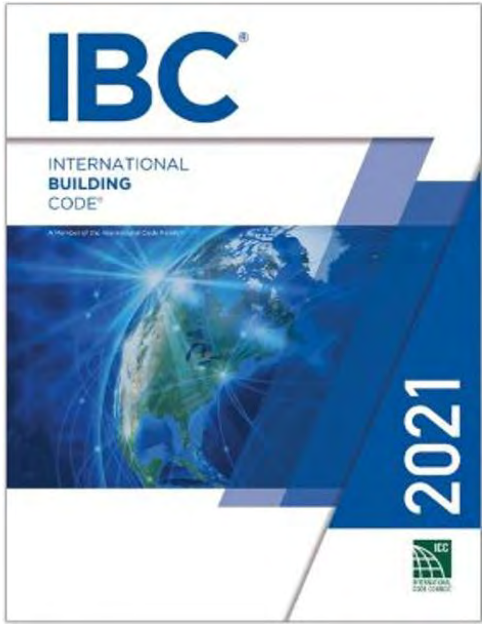
NASA REACT Project - AI SPACEFACTORY

Terrestrial Standard For Structural Loads

- ASCE 7 - Minimum Design Loads and Associated Criteria
- Describes the means for determining structural design loads:
  - dead, live, soil, snow, flood, seismic, wind, and load combinations
- An integral part of structural requirements of building codes in the US
- Essential to practice of civil & structural engineers, architects, etc

<u>Structural Load Criteria is Important for Lunar Design</u>

- Engineers will be employed to design Lunar buildings and infrastructure
- Criteria for determining Lunar structural loads is not currently available
- A preliminary set of Lunar structural load criteria can be created now based on previous research and available Lunar data.
- Additional testing and research will be required in the future



Preliminary Lunar Structural Load Criteria (In-progress)

Lunar Structural Loads Chapters/Topics

- **Combination of Loads** (ASD and LRFD)
- **Dead and Regolith Loads** (self-weight, regolith pressures and bearing)
- **Live Loads** (uniform, human, equipment, vibration)
- **Environmental Loads** (thermal, radiation, etc)
- **Natural Impactor Loads** (micrometeorite Impacts)
- **Artificial Impactor Loads** (vehicular impacts, etc)
- **Artificial Atmospheric Loads** (internal pressure, pressure loss, cyclic effects)
- **Transportation Loads** (autonomous and human driven vehicular loading)
- **Rocket Landing and Launch Loads** (rocket plume effects, lander leg impact)
- **Seismic Design Criteria and Loads** (site parameters, ground accelerations, analysis procedures)
- **Geotechnical Considerations** (regolithworks, retaining, shoring, foundations)
- **Special Considerations** (lunar dust effects and mitigation, etc)

Structural Loads group is searching for for industry review and input for these loading values

Example: Landing Pad Loads

Table 1.0 – Idealized Rocket Plume Loading Values in the Lunar Environment on Engineered Surfaces

(data compiled from available "Payload Users Guide" for CLIP and HLS landers and NASA Apollo Lunar Module values)

Landing Launch Craft Class	Maximum Total Landing or Launch Mass kg (lbs)	Maximum Plume Pressure kPa (psi)	Maximum Plume Temperature °C (°F)	Maximum Plume Heat Flux W/m² (btu)	Figure 1.0 Dimensions m (ft)		
					X_1	X_2	X_3
1 ton	1,000 (2,205)	2.0 (0.3)	3,700 (6,692)	7310 (2320)	0.1 (0.3)	0.2 (0.7)	0.3 (1.0)
5 ton	5,000 (11,024)	6.0 (0.9)	3,800 (6,876)	7510 (2380)	0.3 (1.0)	0.5 (1.6)	1.0 (3.3)
10 ton	10,000 (22,047)	11.0 (1.6)	3,900 (7,052)	7700 (2445)	0.6 (2.0)	1.0 (3.3)	2.0 (6.56)
25 ton	25,000 (55,116)	26.0 (3.8)	4,000 (7,232)	7900 (2505)	1.5 (5.0)	2.5 (8.2)	5.0 (16.4)
50 ton	50,000 (110,232)	51.0 (7.4)	4,100 (7,412)	8100 (2570)	3.0 (9.9)	5.0 (16.4)	10.0 (32.8)
75 ton	75,000 (165,347)	76.0 (11.1)	4,200 (7,592)	8300 (2630)	4.5 (14.8)	7.5 (24.6)	15.0 (49.2)
100 ton	100,000 (220,463)	101.0 (14.7)	4,300 (7,772)	8500 (2695)	6.0 (19.7)	10.0 (32.8)	20.0 (65.6)
500 ton	500,000 (1,102,312)	503.0 (73.0)	4,400 (7,952)	8700 (2755)	15.0 (49.2)	25.0 (82.1)	50.0 (164.1)
1000 ton	1,000,000 (2,204,623)	1,006.0 (146.0)	4,500 (8,132)	8900 (2820)	30.0 (98.4)	50.0 (164.1)	100.0 (328.1)

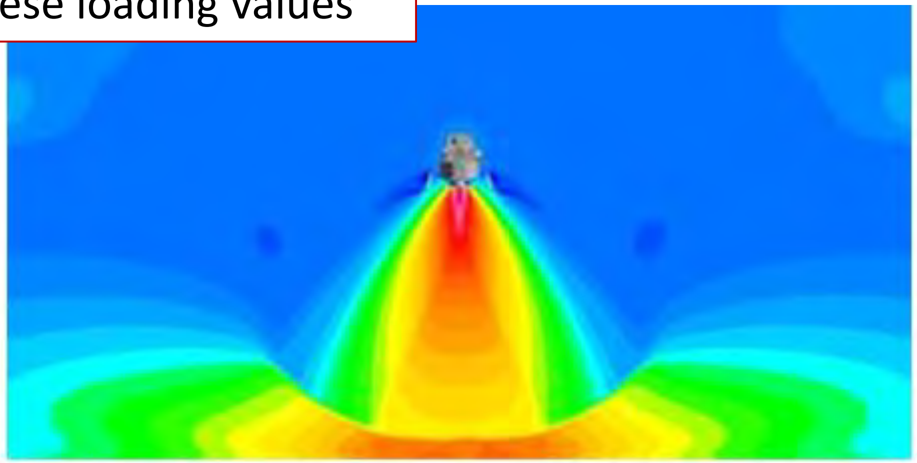


Figure 2: Example Rocket Plume Force/Heat Flux Effect on Horizontal Surface

Credit - NASA

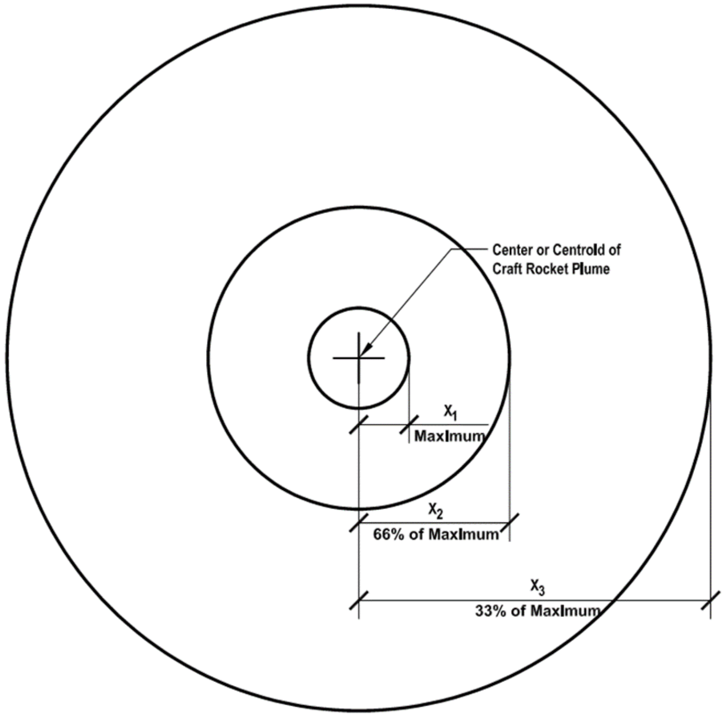


Figure 3: Idealized Plan for Rocket Plume Loading Effect Topography

Example: Seismic Criteria - Lunar Ground Motion Data

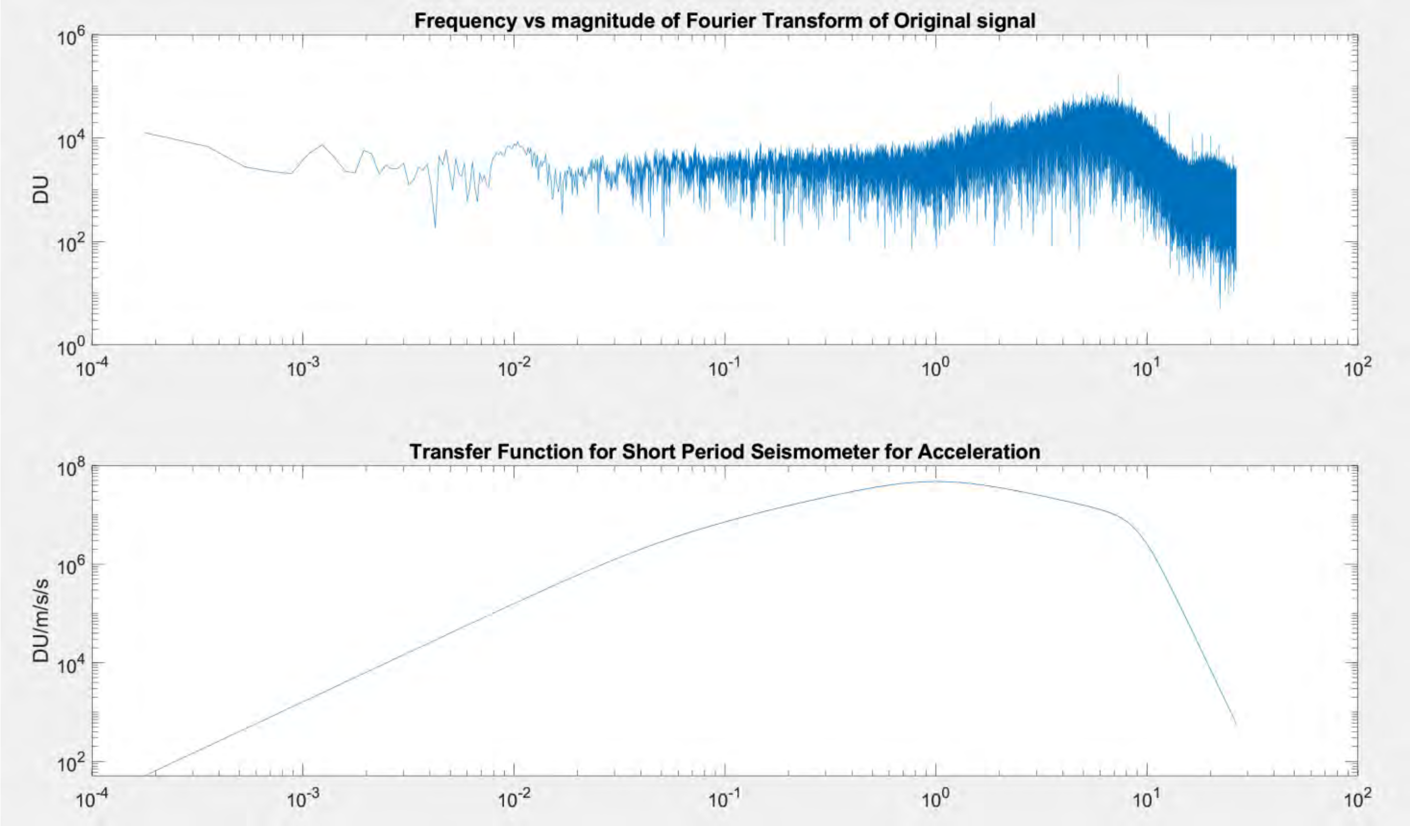


Figure 3: Top - Frequency spectrum of the original signal ; Bottom - Transfer function curve for the Short Period Seismometer for acceleration;

- Analysis of raw data from Apollo Lunar Surface Experimental Package (ALSEP) instruments obtained from NASA Space Science Data Coordinated Archive (NSSDCA)
- Investigation of Shallow Moonquakes based on data gathered from Short-Period Seismometers (SPZ), due to their significant intensity
    - Original unit of measurement = Digital Unit (DU)
    - SPZ designed to detect ground motion of 0.3 nm at 1Hz with peak intensity at 8Hz
    - Transfer function of the short-period sensor $A_{SP}(\omega)$ for acceleration:

$$A_{SP}(\omega) = GG_1G_2S_p(\omega)F_a(\omega)F_l(\omega) \qquad \frac{V}{m/_{s^2}}$$

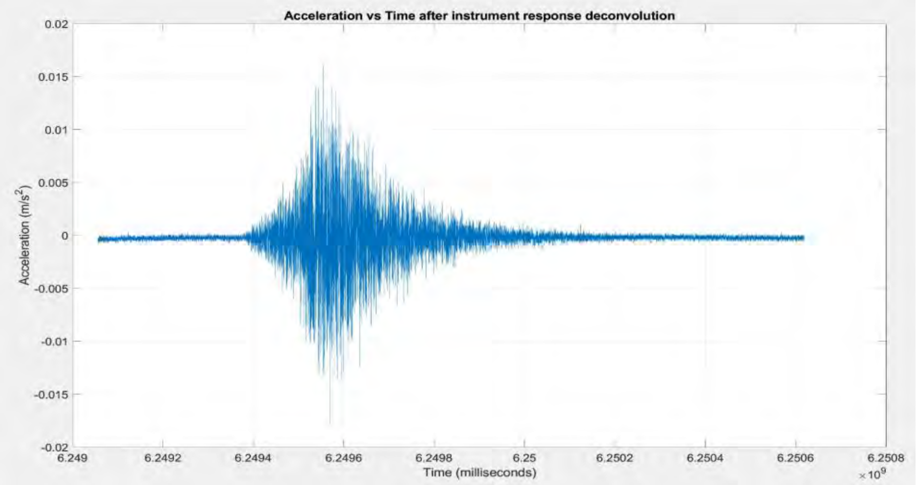


Figure 4: Example of an initial generated ground motion, with amplified ground motion that requires correction and further signal processing

(III) Environmental Considerations

Primary Objectives:

- Present an overview of the lunar environmental conditions that are known and have potential impacts on lunar exploration.
- Present guidelines to account for the environmental conditions in robotic and human lunar infrastructure developments, including the following:
  - Short-term shelters
  - Medium-term and long-term habitats
  - Establishment of permanent lunar bases

Some Environmental Considerations

- Impact of environmental conditions will be different on human shelters and habitats and different for unmanned missions and their related infrastructure

- Generally lunar infrastructure will be inhabitable and their protective elements will differ substantially from elements for habitable structures (needed for short-term, medium-term and long-term human use and habitats)

- Qualification of lunar-destined materials of deployable structures (typical as for any planetary systems)

- Qualification of new materials and protection needed for more complex habitable structures will be very important (ground-based testing and simulation – very difficult and unknown)

Tentative Table of Contents

This chapter will focus on lunar environmental conditions and will have six sections:

1. *Introduction*
2. *Lunar environmental conditions*
3. *Influence of lunar environments on system design and material considerations*
4. *Proposed lunar infrustructure/construction timeline*
5. *Qualification and testing of lunar systems and materials*
6. *Summary, conclusions and recommendations*

Lunar Environment

FOCUS ON: *Lunar environmental conditions*

- Thermal Environment
- Radiation Environment
- Atmosphere and Pressure
- Metereoid Environment
- Lunar Dust
- Moonquakes
- Gravitational Field
- Special Geophysical Features
- Impact of the Lunar Day

Examples Of Critical Environmental Conditions

For Lunar Structures

- Thermal Environment (direct impact on structural loads, protection shielding)
- Radiation Environment (indirect impact on structural loads, direct impact on protection shielding)
- Atmosphere and Pressure (direct impact on structural load and protection shielding)
- Meteoroid Environment (direct impact on protection shielding)
- Lunar Dust (direct impact on protection shielding and mechanisms)

One Of The Most Critical Environments:

Temperature Variation

- Maximum temperature range is 280 K, temperatures are generally very cold
- Affects all phases of utilization of lunar systems and construction
- Technical requirements:
  - Materials must not be brittle above -233°C in permanently shadowed craters ,-188°C at the equator, -85.5°C at mid-latitudes, and -63°C around the poles
  - Insulation/shielding must be provided in phases two and three (for shelters and permanent structures) (Jablonski & Ogden,2008)

(IV) Geotechnic and Foundation

Why Geotechnical and Foundation Guidelines are Critical?

There are several factors to be considered. Below, it is highlighted a summary of them.

- Hazards that exist in an extraterrestrial environment do not occur on Earth. There are no experience with them and yet they must be accounted for in the design.
- Many tools, techniques, and methods we use for geotechnical exploration and ground characterization may not work on the lunar environment.
- Most structures built on the Moon will work mostly in tension, and their foundations may have to be designed to resist large tensile loads. These are not the usual working conditions of buildings on Earth.
- Rock and regolith properties are needed for the design of any geo-structure and foundation in rock or the regolith.
- To determine a set of principles that govern foundation design on the moon, such as ensuring safety, minimizing environmental impact, and promoting sustainable construction practices.
- Standard foundation engineering techniques used on Earth may not be suitable for the moon.
- To recommend suitable foundation types for the lunar environment, such as shallow or deep foundations, or pile foundations.

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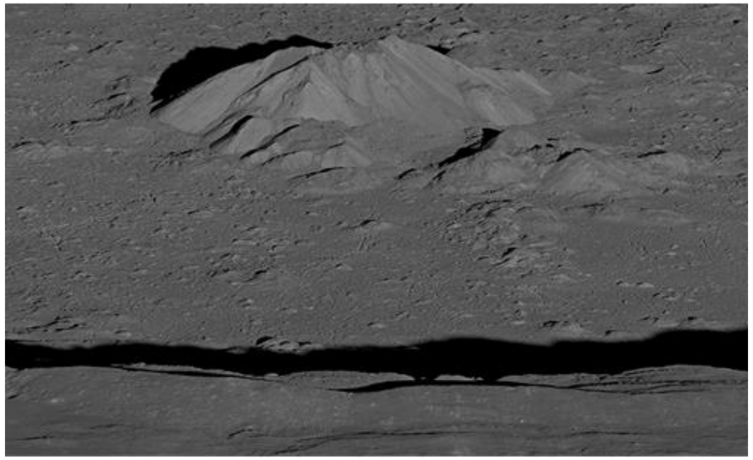
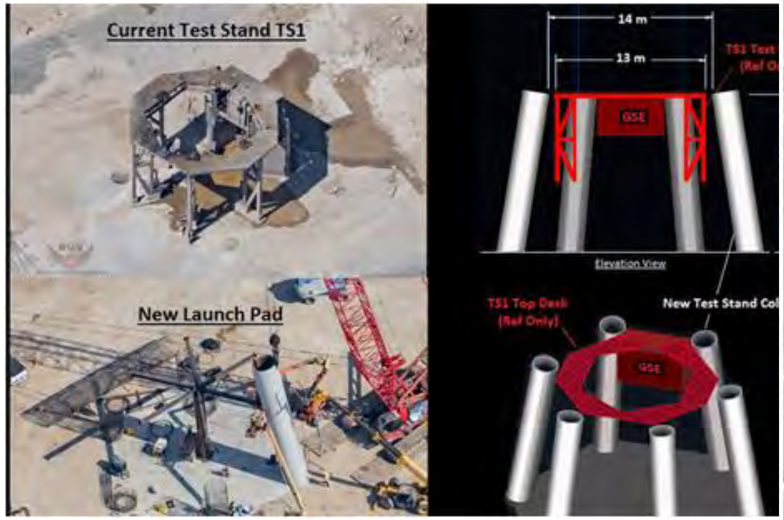
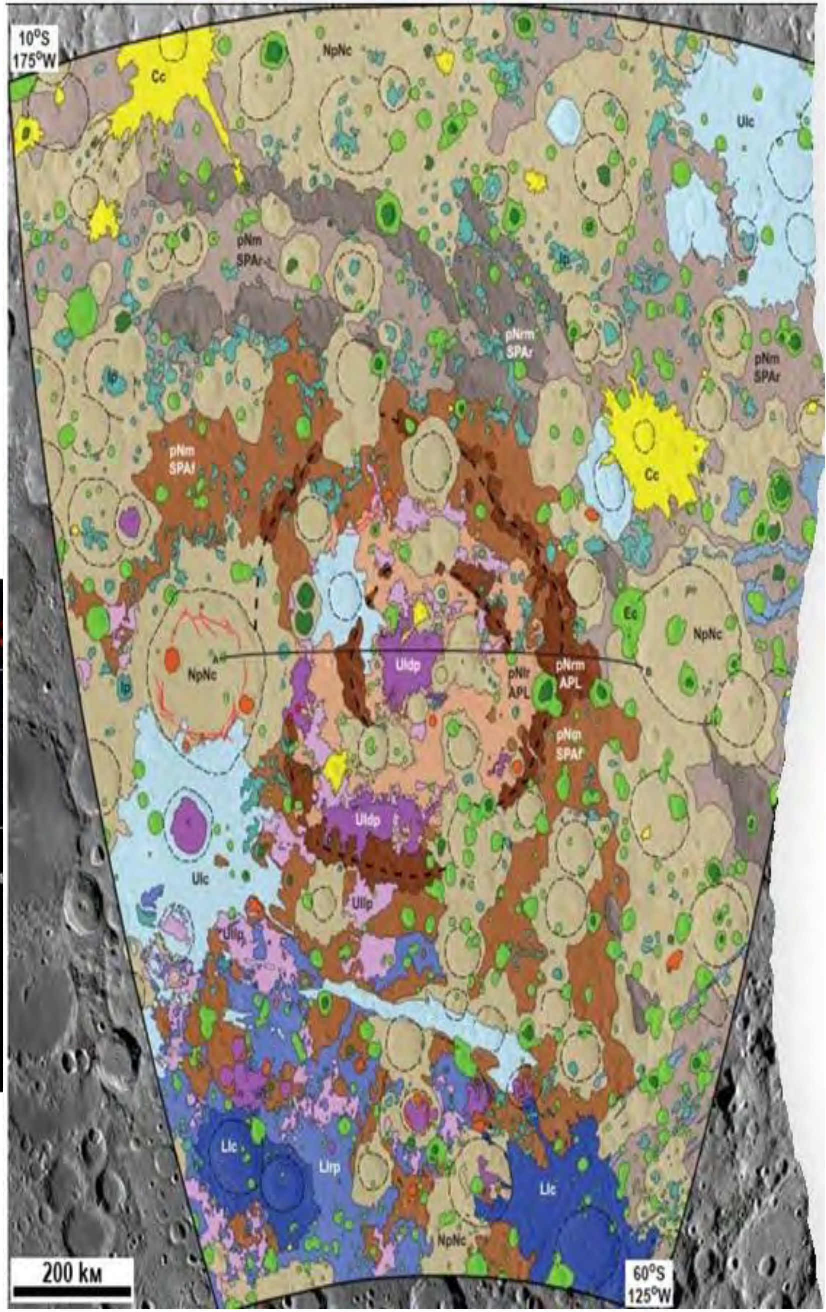
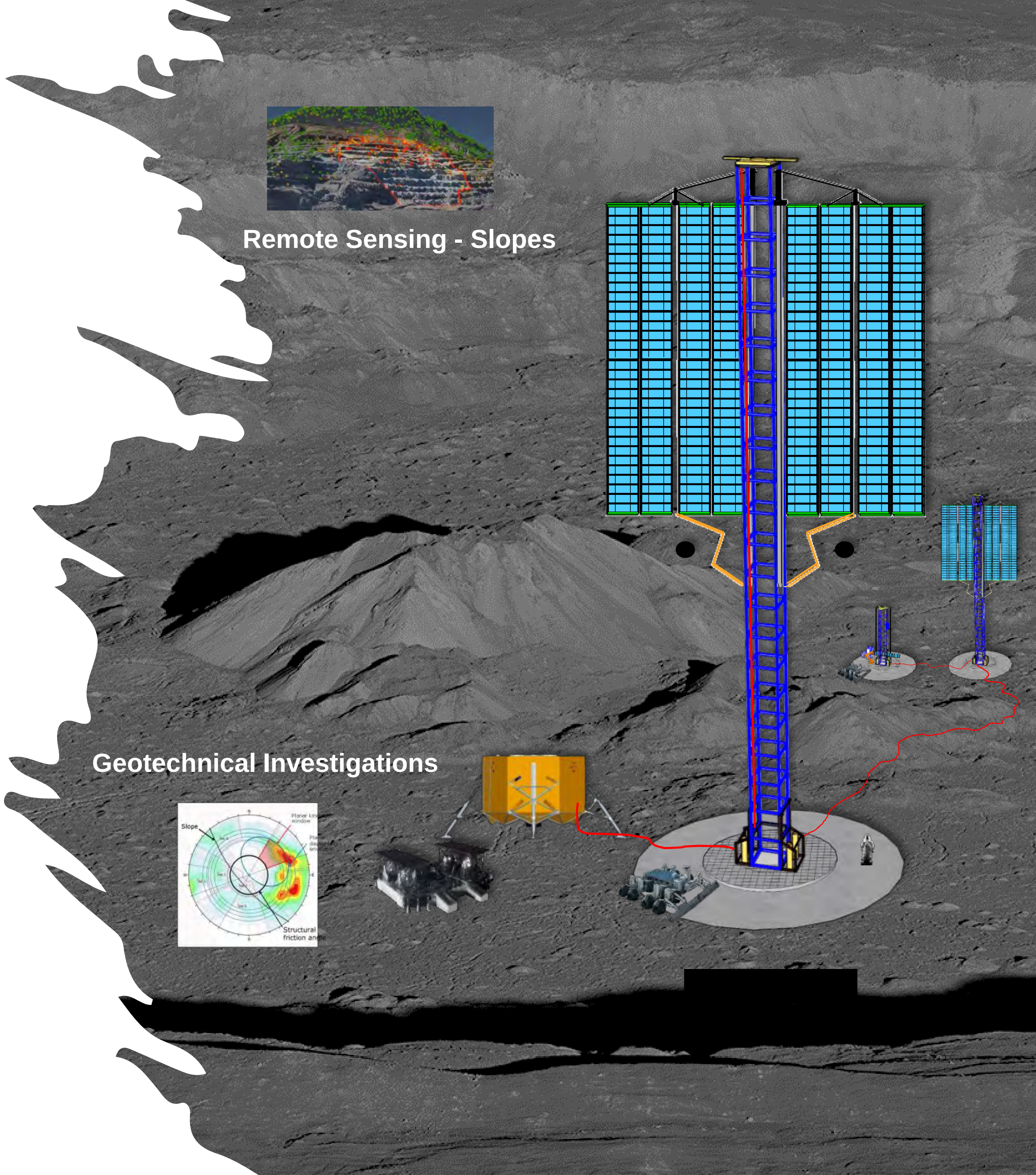






Example -Tall Solar Power Towers

- As an example, the guidelines will recommend the sufficient bearing capacity of foundation to ensure stability of the Towers and to withstand the low gravity and other external factors such as seismic activity.
- The guidelines will develop Limit State Design (serviceability and ultimate) for lunar foundation design.
- The guidelines will include recommendations for designing foundations that can accommodate the low-gravity conditions and dust influences.
- Will provide recommendations on the appropriate foundation depth.
- Ensure that the foundation can support the weight of the Truss-Based Towers, additional equipment and other related secondary structures.



(V) Structures Design, Analysis and Architecture

Objective/Scope

➢ Develop a comprehensive set of guidelines and overview of influencing factors for design/architectural solutions for lunar surface operations considering different types of missions:

- Short-term – Shelters, launching pads, etc. Sortie missions, possible short surface stay (type 1 pressurized structures)
- Mid-term – transitional period from short term to longer term goals. Longer surface stay transitioning to continuous occupancy, (type 1 and 2 pressurized structures combined). Infrastructure for utilities distribution, zoning
- Long-term– permanent human surface presence (type 1, 2 and 3 pressurized structures). Infrastructure for supporting all required operational and habitation needs.

Lunar base Horizon. (Air Force Systems Command, "Lunar Expedition Plan. LUNEX. WDLAR-S-458," 1961)

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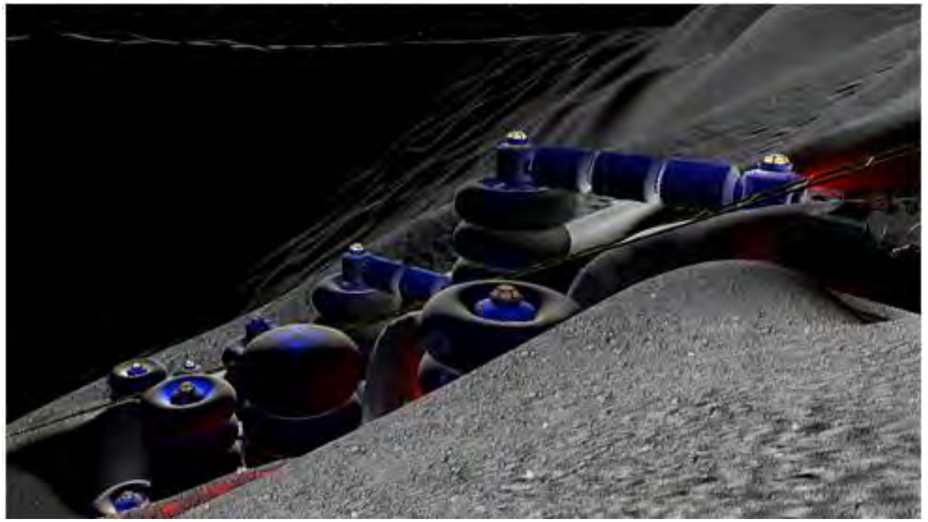
Topics Covered/Contents

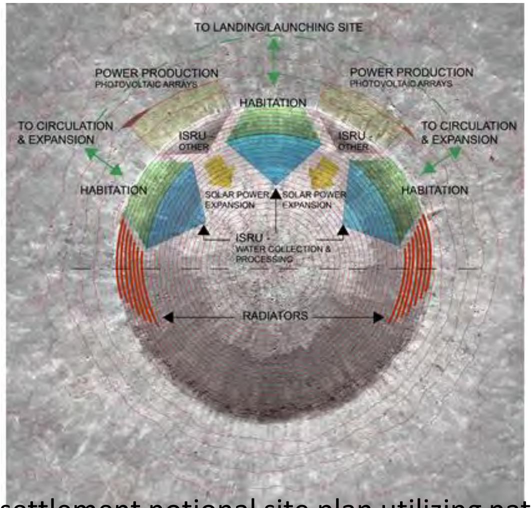
- Impact of Environment
- Master Planning
- Infrastructure, Facilities, and Utilities
- Structural and Architectural Design
- Structural Planning Considerations
- Architectural Planning and Design Considerations
- Building Systems Planning and Design Considerations
- Multi-system Integration and Optimization



Lunar settlement for 80 people on a slope of Shackleton crater. (O. Bannova, Space Architecture: Habitats beyond Planet Earth, DOM publishers, 2021)

Sample: Infrastructure, Facilities, and Utilities

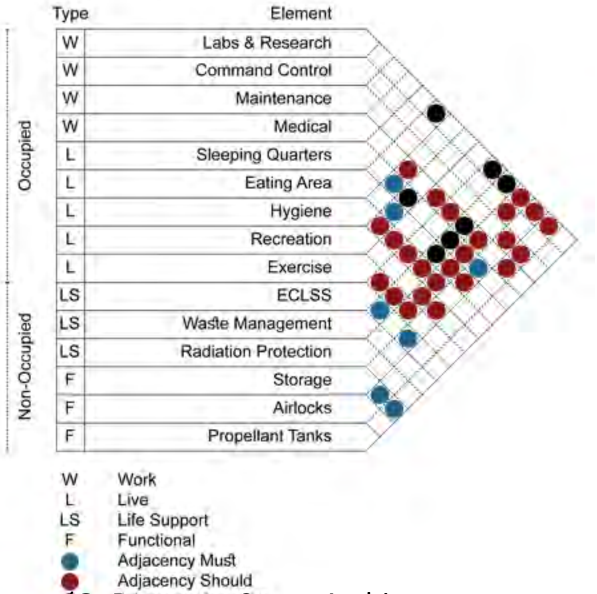
- Landing and Launch structures
- Communications and Power structures
- Transportation structures
- Habitats and other pressurized structures
- Storage and Utilities
- Other public structures
- Mining and excavation sites
- Processing



Moon surface settlement notional site plan utilizing natural protection of a lunar crater relief. (O. Bannova, Space Architecture: Habitats beyond Planet Earth, DOM publishers, 2021)

Sample: Architectural Planning and Design Considerations

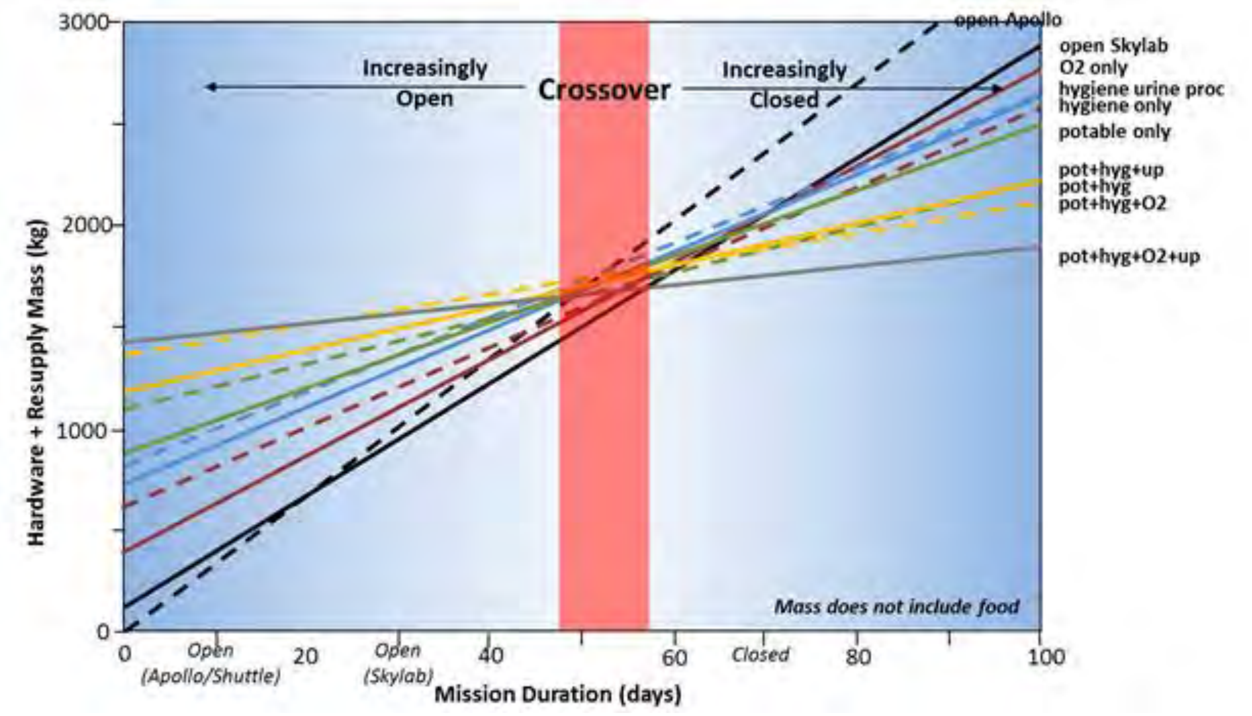
- Types of operations/missions
- Human Needs and Habitability
- Building Types
- Building interfaces and growth strategies
- Architectural Programming
- Contingencies and emergencies responses



Relationships and zoning diagram. (O. Bannova, Space Architecture: Habitats beyond Planet Earth, DOM publishers, 2021)

Sample: Building Systems Planning and Design Considerations (Pressurized system)

- Environmental Control and Life Support Systems (ECLSS)
  - Filtration and Ventilation
  - CO2 Scrubbing
  - O2 Generation
  - Humidity Control
  - Trace Contamination Control
  - Water Processing and Recovery
- Plumbing
- Thermal, Heating and Ventilation
- Lighting and power distribution



Parametric data allows flexibility in space system sizing decisions (S. Haeuplick-Mausburger, O. Bannova, Space Architecture Education for Engineers and Architects, Springer, 2016)

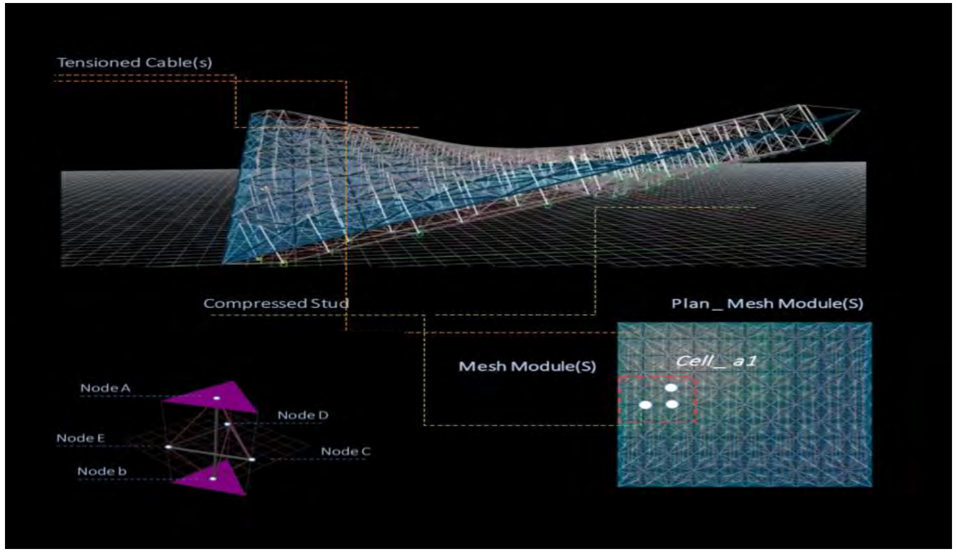
Sample: Structural Analysis and Preliminary Design

Structural System Concepts

- Inflatable Structures
- Deployable Structures
- Cable-strut Systems

Topics included:

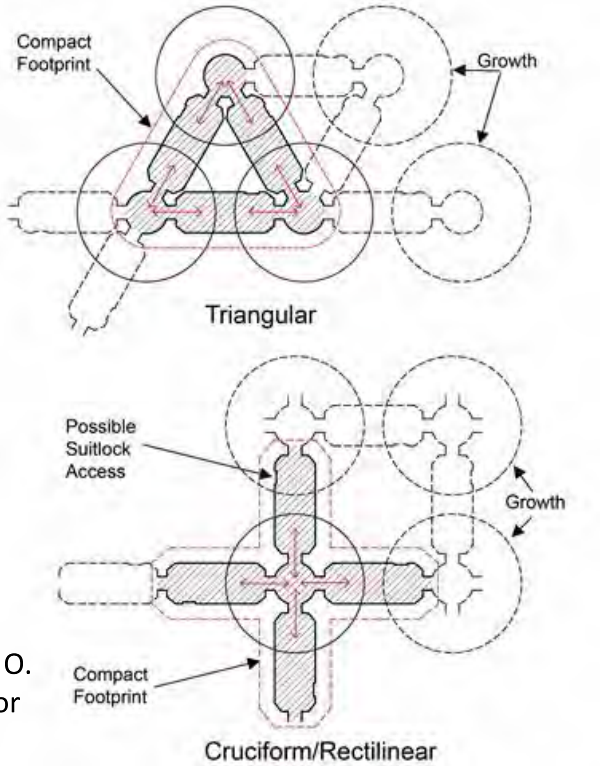
- ➢General Principles
- ➢Analysis and Design
- ➢Loads and Load Combinations
- ➢Modeling and Analysis Types



Credit: P. Capoini, Università degli studi di Roma La Sapienza/University of Miami

Sample: Multi-system Integration and Optimization

- Habitat/Facility System Requirements
- Design Concepts
- Multi-functional Spatial Integration



Expansion schemes based on initial base configuration. (S. Haeuplick-Mausburger, O. Bannova, Space Architecture Education for Engineers and Architects, Springer, 2016)

Participating Members/Individuals

- Ramesh B. Malla, Ph.D., F. ASCE, F. EMI, A.F. AIAA, Univ. of Connecticut, Storrs, CT (**Chair**)
- Hamid Adib, Ph.D., P.E., F. ASCE, F. SEI, Jacobs, Inc., New York, NY (*Lead: Structures Design, Analysis and Architecture)*
- Ramiro Besada, Burns & McDonnell, Kansas City, MO (*Co-Lead, Construction & Materials)*
- Roberto de Moraes, Director of Tunnels AECOM, CA (*Co-Lead, Geotechnical and Foundation)*
- Alexander Jablonski, Ph.D., P. Eng., Canadian Space Agency; Ottawa, Canada *(Co-Lead, Environmental Considerations)*
- Kin F. Man, Ph.D., NASA Jet Propulsion Laboratory, Pasadena, CA, USA *(Co-Lead, Environmental Consideration)*
- Pooneh Maghoul, Ph.D., Polytechnique Montréal, Montreal, Canada *(Co-Lead, Geotechnical and Foundation)*
- Naveen Kumar Muthumanickam, National Renewable Engineering Laboratory (NREL), Golden, *CO (Co-Lead, Construction & Materials)*
- Stephen J. Pfund, LERA Consulting Structural Engineers, New York, NY (*Lead: Design Loads*)
- Nipesh Pradhananga, Ph.D., P.E., Florida International University, Miami, FL (*Co-Lead, Construction & Materials)*

Participating Members/Individuals (Cont'd…)

- Juan Agui, Ph.D., NASA Glenn Research Center, Cleveland, OH
- Olga Bannova, Ph.D., University of Houston, TX
- Andreas Becker, Dr.-Ing., University of Kaiserslautern, Kaiserslautern, Germany
- Nerma Caluk, Florida International University, Miami, FL (Ph,D, Student)
- Peter J. Carrato, Ph.D., S.E., P.E., C.Eng, F. ASCE, F. ICE, F.ABET F.ACI, Bechtel Corp.(Retired)
- R. Keith Churchill, Chief Innovation Officer Bechtel Corp., Reston, VA
- Toni Curate, Ph.D., NASA Kennedy Space Center, FL
- Christopher Dreyer, Colorado School of Mines, Golden, CO
- Nathan Gelino, Principal Investigator NASA Kennedy Space Center, FL
- Leslie Gertsch, Ph.D., Missouri University of Science and Technology, Rolla, MO
- Jeff Hopkins, FarSight Technologies, LLC, League City, TX
- Ian Jehn, P.E., S.E., M.I. Colorado School of Mines, Golden, CO
- Yong-Rak Kim, Ph.D., Texas A&M University, College Station, TX
- Sudarshan Krishnan, Ph.D., University of Illinois, Urbana-Champaign, IL
- Robert Moses, Ph.D.; Commercial Innovation Strategy Lead Axiom Space

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Participating Members/Individuals (Cont'd)

- Robert Mueller, NASA Kennedy Space Center, FL
- Clive R. Neal, Ph.D., University of Notre Dame, Notre Dame, IN
- Landolf Rhode-Barbarigos, Ph.D. University of Miami, Coral Gables, FL
- Melissa Sampson, Ph.D., Lockheed Martin, Boulder, CO
- Gerald (Jerry) Sanders, NASA Headquarters, Washington, D.C..
- Krzysztof (Chris) Skonieczny, Ph.D. Concordia University, Montreal, Canada
- Karol Seeryn, Ph.D. Polish Academy of Sciences, Warsaw, Poland
- Sachin Tripathi, University of Connecticut, Storrs, CT (Ph,D, Student)
- Sushrut Vaidya, Ph.D., Univ. of Connecticut, Storrs, CT
- Matthew Waterman, Bechtel Corp., Reston, VA
- Paul van Susante, Ph.D., Michigan Technological University, Houghton, MI
- Kris Zacny, Ph.D., Honeybee Robotics Space Mechanism Systems, Pasadena, CA
- Hongyu Zhou, Ph.D., Univ. of Tennessee, Knoxville, TN

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