Moon Village

What Could Happen in Your Lifetime

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Living in Space – Innovate Pasadena

Jet Propulsion Laboratory
California Institute of Technology

Moon Village

Moon Village concept, 2015

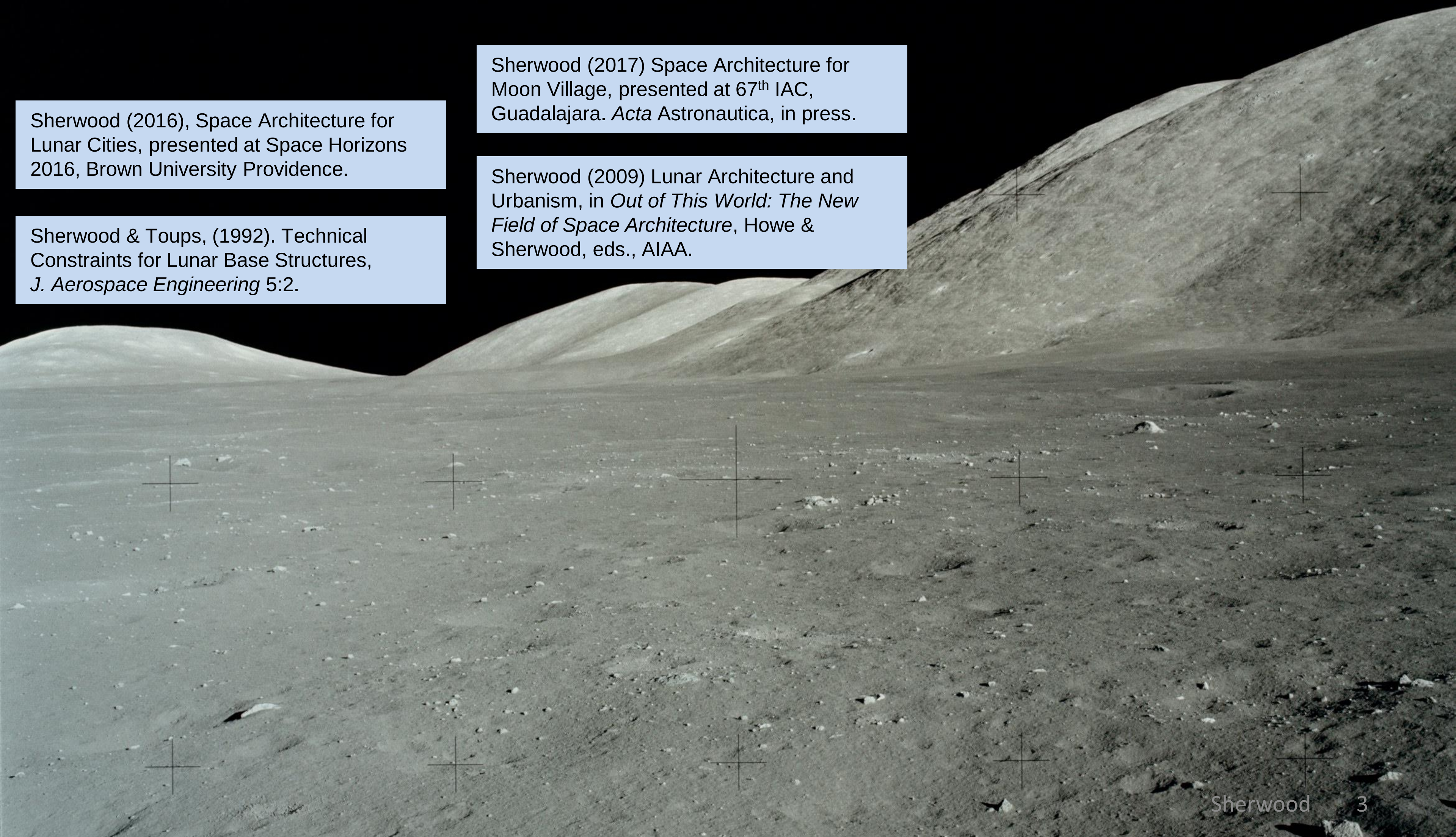
Multiple actors
…with independent goals

Shared location
…and synergistic actions

More practical for the spacefaring community than humans to Mars

Johann-Dietrich Wörner
Director General, ESA

Unlikely Place for a Village?



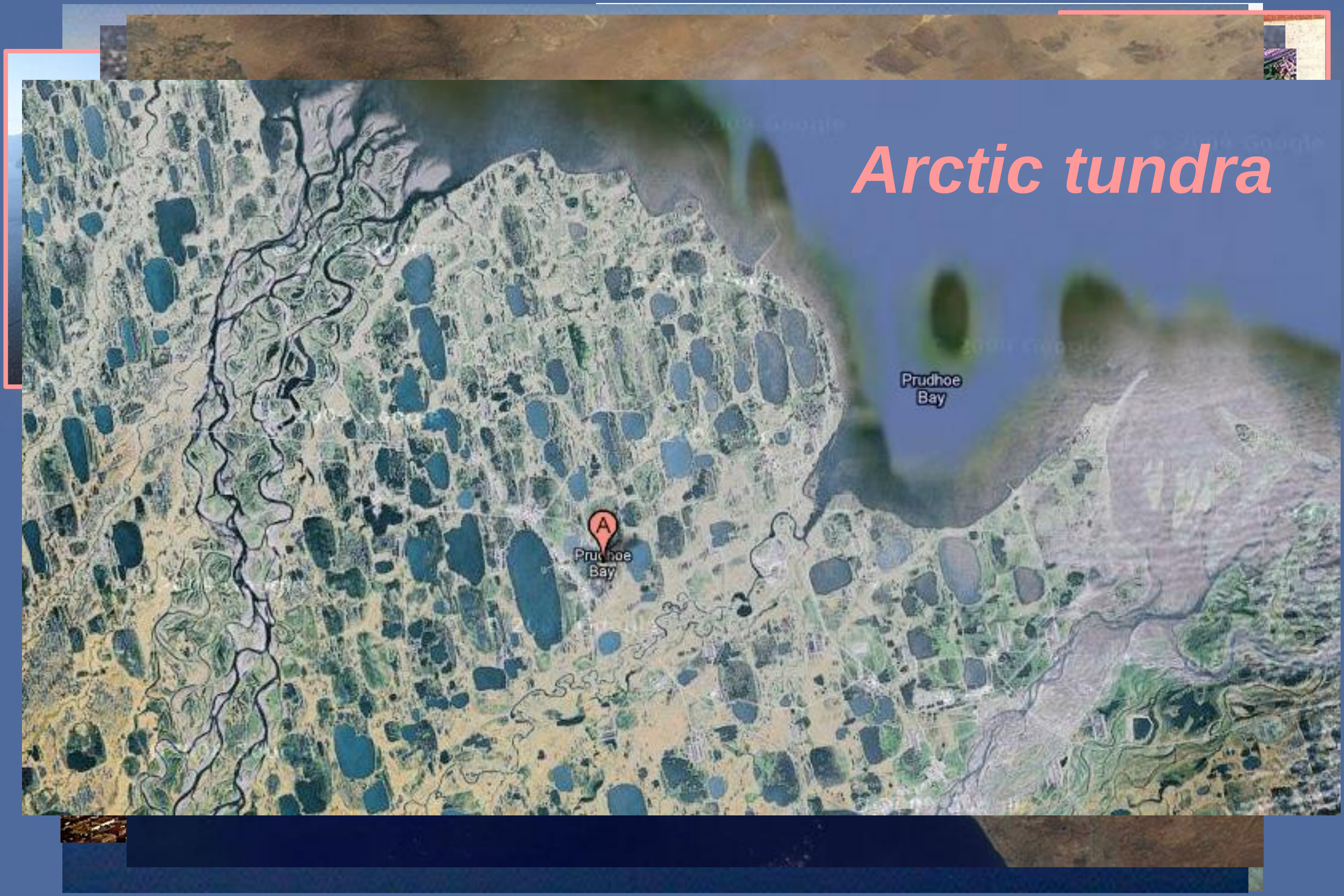
Sherwood (2016), Space Architecture for Lunar Cities, presented at Space Horizons 2016, Brown University Providence.

Sherwood & Toups, (1992). Technical Constraints for Lunar Base Structures, *J. Aerospace Engineering* 5:2.

Sherwood (2017) Space Architecture for Moon Village, presented at 67th IAC, Guadalajara. *Acta* Astronautica, in press.

Sherwood (2009) Lunar Architecture and Urbanism, in *Out of This World: The New Field of Space Architecture*, Howe & Sherwood, eds., AIAA.

Cities arise in unlikely places



Who would pay for this to happen on another planet?

A MoonVillage can drive all four goals

Explore

Exploit

Experience

Expand

Six principles govern MoonVillage activities

Science

- Lunar science is fundamental
- We know essentially nothing about 1/6 g

Practicum

- Practical knowledge is pivotal
- Expert services can be sold

Resources

- Exports enable growth

Urbanism

- A settlement orientation changes everything

Finding #1. A Moon Village is feasible, but more complex than ISS

- Power
- Laboratories
- Habitats
- ETO-RTE “shuttle”

- Power
- Laboratories
- Habitats
- ETO-RTE “shuttle”
- Trans-orbital “shuttle”
- Lander-Ascent “shuttle”
- Surface mobility & construction
- Resource utilization

Finding #2. Roles for all players, at all scales

Group I — "Big Four" Government Agencies

esa
NASA
РОСКОСМОС
CNSA

Group II — Smaller and niche spacefaring governments

JAXA
CSA ASC
وكالة الإمارات للفضاء
UAE SPACE AGENCY
इसरो isro
KARI
Korea Aerospace Research Institute
DLR
cnes
AEB
AGÊNCIA ESPACIAL BRASILEIRA

Group III

- OldSpace companies
- NewSpace companies

LOCKHEED MARTIN
THALES
Orbital ATK
BOEING
NORTHROP GRUMMAN
MDA
AIRBUS
BIGELOW
PLANETARY RESOURCES
SPACEX
ASTROBOTIC
DSI
DEEP SPACE INDUSTRIES

Finding #4. Growth requires export

Information	Knowledge about the Moon Science data generated on the Moon	Science sponsors $
	Lessons learned about operating on the Moon	Potentially: spacefaring customers (human-mission users of space transportation and space industries) $$
Oxygen, hydrogen	Propellant	
Other volatiles, metals, raw materials	Water, breathing air, biomass. Shielding, reaction mass. Industrial products.	
Minerals	Rare Earth Elements	Terrestrial manufacturing industries $$$$
	^{3}He	Potentially: terrestrial energy industry
Entertainment	Novel sports and art	Terrestrial media markets
Experience	Non-specialist guests, immigrants	Tourism, emigration

Finding #6. Practicum precedes industrial viability

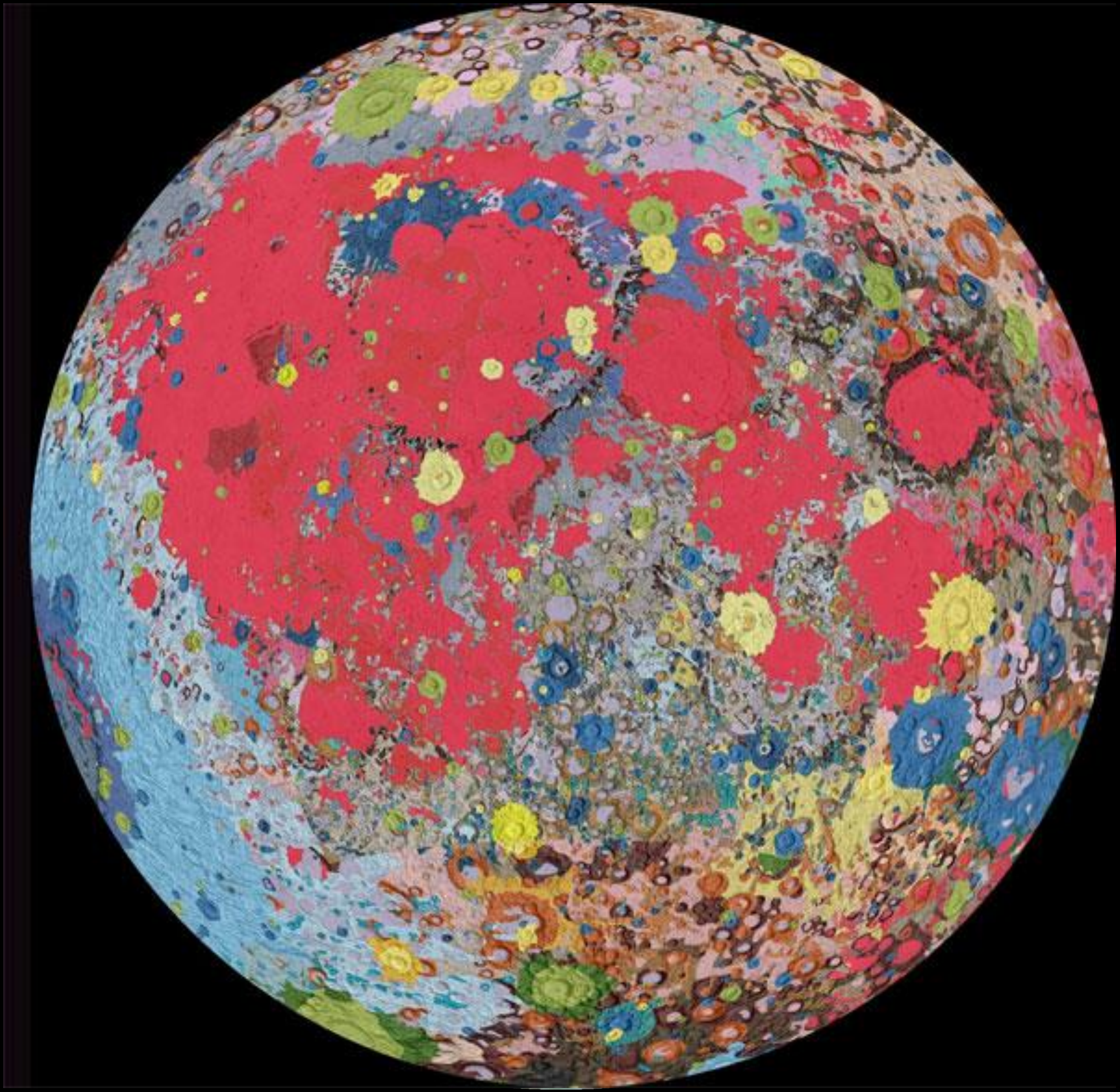
Activity, Purpose, Product	Explanation & Examples	Significance
Practicum	Learning the basics about how human systems can function in the lunar environment	Essential, marketable pragmatic experience in making things work, including keeping systems running and people healthy and positive in this unprecedented place
Environmental management	Dust control and tribological management. Radiation shielding. Impact shielding. Thermal regulation. Power management. Safety.	Learning to operate within or despite **native conditions**, and how to use them to inspire and enable elegant designs and operations.
Industrial operations	Adaptation, practice, refinement, scaleup, and management of safe and predictable operations to produce and manage power, control environmental conditions, and make engineering materials	Required for permanence and **growth of large-scale operations**
Kitchen science	"How to cook an omelette and mix a martini." Hygiene and grooming. Safety. Cleaning. Repairing. Art.	Enables development of **quotidian activities** (substance behaviors, processes, movement, technique, design and use of specialized tools and equipment, safety). Stimulates creative innovation and art.
Habitation operations	Life support and environmental control. Safety. Maintenance. Architecture. Private and Public accommodation. Sports and recreation.	Required to assure lifesafety and routine operations at all habitation scales. Required for scaling up from single-ship crews **toward settlement populations** (~100 – 1000).
Urban operations	Utilities: air, water, power, network temperature, sewer, recycling. Safety of construction and operations. Transportation of goods and people. Supply chain. Human assembly. Sports and recreation. Zoning. Security.	Required to enable **social living** in an intrinsically lethal place.
Exploration preparation	Researching, developing, testing, and rehearsing systems and operations for deep-space exploration.	Required for **humans to Mars** or other places more than a few days away from Earth.

Findings #7. and #8.

Government investment is enabling.

Commercial enterprise controls growth.

	Phase 1 Exploratory	**Phase 2** Experimental	**Phase 3** Industrial Scaleup
Group I e.g., ESA, CNSA, RSA, NASA	Inventory and understand lunar environments and resources	Determine potential benefits and costs of lunar utilization scenarios	Maintain operating environment that allows commercial and public activities
Group II e.g., Japan, Canada, India, Korea, Brazil, UAE	Enlarge and diversify the set of locations explored	Conduct independent research	Diversify interplanetary economy
Group III Commercial 1.Oldspace 2.Newspace	Sell basic services to Groups I and II (e.g., access, information, samples)	Sell routine operating services to Groups I, II, and III (e.g., logistics, maintenance) Pilot marketable production: water, propellant, mineral resources	Sell lunar products and infrastructure access and services to Groups I, II, and III (e.g., water, oxygen, propellants; power, networking, leased space and equipment)



BACKUP

Eight findings: Participation in a MoonVillage

1. Technically feasible, it will be more complex than the ISS.
2. Significant opportunities exist at all evolutionary scales.
3. Mixed-use space business park model is essential.
4. Growth depends on exporting lunar material products. Growth rate depends on exporting to terrestrial industries.
5. “Lunar urbanism” hinges on industrial-scale operations, and dramatically drives technology requirements.
6. Industrial viability cannot be predicted without significant in situ operations first; we lack easily available data.
7. Government investment in lunar surface ops is enabling. U.S. government likely holds the greatest leverage.
8. Only the prospect of commercial interplanetary business can attract capital beyond government funding

5. Urbanism hinges on industrial scale

Location	Essentially permanent
Scale of operation	Large – Permanent Governing factor: profitability of exports
Type of Crew	Public Governance, law enforcement, administrative, commercial, retail, maintenance, medical, social services…
Size and focus of population	$10^3 - 10^6$ citizens exploit specialized niches in a robust urban ecology
Technology type	Architectural, meeting public and domestic needs, safety and security Mass produced, adaptable, recylcable Extensible
Life Support	Biological and buffered, with mechanical emergency temporary backup

Physical Environmental Constraints

Pressure differential	Negligible outside atmosphere – hard vacuum for free Habitable systems must withstand 70-100 kPa (10-15 psi) across entire enclosing surface, plus safety factors Glass manufactured in situ can approach its theoretical strength
Diurnal cycle / Temperature extremes	Synodic period 29.53 Earth days. (at equator, almost 15 hrs sunlight and 15 hrs darkness) Nearside, Full Earth ~50x brighter than Full Moon appears from Earth Temperature range: -171 to 111° C. Temperature falls ~5° /hr at sunset.
Radiation	Continuous Galactic Cosmic Radiation and episodic high-energy solar protons, both isotropic from overhead hemisphere
Micrometeoroids	Up to full encounter velocity of ~20 km/s Sensitive surfaces require shielding
Lunar gravity	1.62 m/s^2 at surface (~ 1/6 g) Gravity-stabilized operations. “Slender-span” structures possible.
Substrate mechanics / dynamics	Upper few 100s m are essentially rubble; few outcrops. 2-30-m thick regolith layer (5-10 m in mare regions) Bulk density very low (0.8-1.0 t/m^3) in uppermost mm, but reaches 1.4-2.2 t/m^3 at 3-m depth. Relative density approaches 100% just a few meters down. 30-50° angle of internal friction. More cohesive than most terrestrial soils (0.1-1.0 kN/m^2). Seismic disturbances can be neglected for structures
Dust composition / behavior	50% of regolith comprises particles finer than 70 µm (unresolvable by naked eye) Abrasive, electrostatically “sticky” in hard vacuum Macroscopically, clumps together like damp beach sand
Available material combinations	>98% of surface material comprises O, Si, Mg, Fe (9-14%), Ca, Al (9-18%), Ti (9-18%) in mare regions Bulk deficient in CHNPS (elements required for biomass) Regolith enriched in H from eons of solar wind Glasses are found naturally, and can be made from available CaO and SiO_2

Operations Constraints

Heat rejection	Vacuum is a superb insulator. Regolith is a poor conductor. Rejecting low-grade heat during lunar day is difficult Cryogen storage requires temperatures down to 20 K. Basalt melts at around 1500 K.
Radiation safe-haven	Needed for all occupants, up to a few days at a time
Human mobility envelope	2.5-m headroom might be necessary (20-45 degree body inclination, 1.25-4 m/s running speed). New standards for riser/tread ratio and dimensions.
Habitat internal outgassing, and health environment	Restricted materials list In situ vitreous and rock surfaces; radon risk unknown
Accommodation of robotic assembly, operations, and maintenance	Lunar architecture will predominantly be built, operated, and maintained by machines. Many kinds and degrees of autonomy.
Joining techniques	Tolerant, robust, and repeatable in situ joining techniques are an enabling major development
Retrofitting	High premium on reusing available equipment For economy, systems must be designed to be taken apart, reconfigured, re-outfitted, and re-verified
Expansion	For economy, architecture must be scarred for open-ended construction, including radiation shielding
Disposal	Recycling, stockpiling engineering materials Long-term storage of nuclear waste
Staging environments	Ground processing on Earth, Earth-to-orbit launch, LEO including debris, trans-GEO including van Allen belts, high-thrust lunar landing

Science Activities

Activity, Purpose, Product	Explanation & Examples	Significance
Scientific investigation	Understanding natural processes that constrain what the Moon offers and allows us to do	Governs all other activities
Environmental context of the Moon	Space environment surrounding the Moon. Moon's dynamic exosphere.	Defines **fundamental engineering parameters**: temperature, radiation, insolation, tribology… Constrains **volatiles**: sources, distribution, state, mobility.
Lunar geology	Geophysics of the Moon as a telluric planetary body (formation, differentiation, volcanism, tectonism, and exogenic modification)	Constrains **solid materials** (abundance, form)
	Geochemistry of areas of interest (elemental composition, mineralogy, weathering)	Constrains **accessible solid** and **volatile materials** including all **ores (**states, form, mixtures)
	Surface modification processes (seismic activity, thermal cycling, meteorite gardening, space weathering)	Surface states, **mechanical properties**, chemical and physical durability.
Lunar-based science operations	Use of radio-quiet Farside to emplace, maintain, and permanently operate large radio astronomy antenna arrays	Unique solar system location enables a **new window into the universe**
1/6-g physics	Behavior of granular materials, fluids, and plasmas (including flame) on the Moon	**Unprecedented gravity regime** reshapes all familiar natural physical behaviors
1/6-g and hermetic biology	Short-term and long-term adaptation of macromolecules, organisms from all kingdoms of Earth life including humans and human microbiota, and ecologies. Psychology and sociology.	Required for operationally useful human residence time and… Establishment, operation, and perpetuation of a **closed ecology** that sustains humans.

Resource Utilization Activities

Activity, Purpose, Product	Explanation & Examples	Significance
Resource utilization	Use of native material to obtain basic resources and produce engineering materials at all scales	Essential, marketable activities for human and machine activity to grow beyond exploration-scale
Mining	**Volatiles** from heated regolith: water, oxygen, hydrogen, carbon, nitrogen, phosphorus, and sulfur (adsorbed from solar wind and deposited by impactors)	Breathing air and drinking water. Biomass. Propellant. Radiation shielding. Industrial processes.
	Iron from magnetic beneficiation of regolith: native iron grains in regolith (reduced by solar-wind hydrogen)	Widely useful metal from a unique resource on the airless Moon.
	Regolith	Beneficiation yields raw material for dust control and siteworks: berms, paving gravel, compacted regolith, radiation shielding, and feedstock for sintered and cast-glass products.
	Minerals: from crystals and chemical complexes comprising rock	Construction materials. Metals, semiconductors, trace elements.
Processing	Safe physical, thermal and chemical beneficiation and conversion, to produce industrial feedstock	Required for design and operation of **in situ manufacturing** equipment and processes.
Manufacture of substances	Safe production, handling, storage, and transportation (gases, plasmas, liquids, solids).	Basis of **any products** made in situ.
Manufacture of structure elements	Structural sections, concrete. Tanks, piping. Pressure-vessel components and systems. Safety.	Required to build **Type-III structures**, which are in turn required for cost-efficient growth.

Urban Development Activities

Activity, Purpose, Product		Explanation & Examples	Significance
Urban development		Applying the practicum, to scale up the use of local resources, to support diversifying activities by a growing human population.	Marketable activities required to plan, build, and operate human settlements at scales from camp to city.
Internal	Site	Surveying, site planning. Site construction (grading, excavation, deposition, paving, foundations, stabilization, sealing) Infrastructure emplacement, recycling	Foundation for all **sessile architecture** and **traffic**.
	Building	Methods for design, fabrication, assembly, construction, expansion, test, verification, deconstruction.	Required to build and certify **Type-II and Type-III structures** (including habitats).
	Habitation	Apartments, offices, assembly and recreation spaces, laboratories and industrial plants, farms and gardens, maintenance spaces, transportation systems.	Essential building units of all **occupied volumes** for diverse purposes.
	Life support	Biological conditioning of air and water. Operational buffers. Physicochemical emergency backup systems.	Required to **sustain people** indefinitely.
	Food sourcing	Production, processing, packaging, distribution, and composting of food.	
	Waste processing	Collection, stabilization, packaging, transportation, recycling, repurposing, decomposition (gray water, sewage, biohazards, refuse, food byproducts, industrial byproducts, manufactured products)	
	Maintenance	Routine access, inspection, cleaning, troubleshooting, disassembly, repair, upgrade, reassembly, test, verification.	
	Support services	Retail (shopping, grooming, laundry, tailoring) Health care, funeral.	
	Social services	Security, safety. Education, training. Governance.	
	Recreation	Open spaces, parks, assembly halls, arenas, theaters, sport courts, pools, restaurants, bars, clubs.	
Export	Information	Knowledge about the Moon.	Science sponsors.
		Science data generated on the Moon.	
		Lessons learned about operating on the Moon.	Potentially, spacefaring customers (space transportation, human mission, and space industries).
	Oxygen, hydrogen	Propellant.	
	Volatiles, metals, raw materials	Water, breathing air, biomass. Shielding, reaction mass. Industrial products.	
	Minerals	Rare Earth Elements	Terrestrial manufacturing industries
		^3He	Potentially, terrestrial energy industry
	Entertainment	Novel sports and art	Terrestrial media markets
	Experience	Hosting non-specialist guests.	Tourism

The Four Goals Are Really Different

Option	Purpose	Myth	Needs (+ $\$10^{11}$ over 40 yr)	Yields	2050 Space Population
Explore Mars	Extend direct human experience as far as possible	Hero (Lewis and Clark)	Public commitment sustained over several decades	Cultural achievement: setting foot on Mars	Six international civil servants
Settle the Moon	Establish humanity as a two-planet species	Pioneer (Heinlein)	• Routine heavy traffic to lunar surface • Use of lunar resources	"Living off the land" in space	10^3 citizens raising families off-world
Accelerate space passenger travel	Create new travel-related industries	Jet set (Branson)	"Four 9s" reliability launch and entry	• Highly reliable, reusable space vehicles • 1-hr intercontinental travel	10^3 crew + 10^5 citizens in LEO every year
Enable space solar power for Earth	Prepare for post-petroleum age with minimal disruption	Green	Public-private and inter-Agency partnerships	• Energy-abundant future • Economical heavy-lift launch	10^2 skilled workers in GEO

Sherwood, B., "Comparing Future Options for Human Space Flight," *Acta Astronautica* 69, 2011, pp. 346–353