Special Presentations

In Situ Resources for Lunar Base Applications

Haym Benaroya
Department of Mechanical and Aerospace Engineering, Rutgers University

Introduction

Lunar resources have been cited either as an economic driver to justify a return to the Moon or as being useful in the creation and maintenance of a lunar civilization. Except for He_3 as a fusion fuel, the former is unlikely.

Lunar Composition

- 45% chemically bound oxygen
- Also: silicon, iron, calcium, aluminum, magnesium, titanium

  89% { SiO_2-45%, TiO_2-2.5%, Al_2O_3-9%
  FeO-22%, MnO-0.3%, CaO-10%
- And: helium, hydrogen, nitrogen, carbon

Robotics vs. Manned

- The mix of automated and human-based construction and maintenance for a first base will be heavily dominated by the latter. With time, more will be borne by robotics.
- Primary structures of an initial lunar base will likely be prefabricated.
- Robots + regolith = short life and low reliability

Lunar Base Structural Needs

- Shelter for humans and machines
- For humans (and other living things): pressurized, radiation-free volumes
- For machines: depending on the item, various needs can be anticipated (e.g., dust-free volumes, radiation-free volumes, pressurized volumes)
- Some shielding against micrometeorites
- Internal pressures drive structural design
- Power generation and distribution systems
- "Life" systems: water, sewage, air
- Roads and foundations
- Landings/launching pads
- Manufacturing facilities

Resources and Their Uses

- Lunar oxygen: propellant, life support
- Iron, aluminum, titanium: structural elements
- Magnesium: less strong structural elements
- Regolith: sintered blocks

Potential Applications

- Structural beams, rods, plates, cables
- Cast shapes for anchors, fasteners, bricks, flywheels, furniture
- Solar cells, wires for power generation and distribution
- Pipes and storage vessels for fuel, water, and other fluids
- Roads, foundations, shielding
- Spray coatings or linings for buildings
- Powdered metals for rocket fuels, insulation
- Fabrication in large quantities can be a difficult engineering problem in terms of materials handling and heat dissipation

Related Issues: Reliability

- Design life and reliability are very difficult to estimate for the lunar site
- It is imperative to develop techniques that allow such estimates to be made, especially for components created from *in situ* material

Concluding Thoughts

- Key components of a lunar outpost can be built from *in situ* resources (2nd generation)
- Robotic construction needs advances (3rd generation)

Framework for Building Systems

H. Benaryoya

Types of Applications

Habitat/Constructed Volume Types

- Pressurized (living and working)
- Agriculture
- Airlocks: ingress/egress
- Temporary storm shelters for emergencies and radiation
- Open (unpressurized) volumes

Storage Facilities/Shelters

- Cryogenic (fuels and science)
- Hazardous materials
- General supplies
- Surface equipment storage
- Servicing and maintenance
- Temporary protective structures

Supporting Infrastructure

- Foundations/roadbeds/launchpads
- Communication towers and antennas
- Waste management/life support
- Power generation, conditioning and distribution
- Mobile systems
- Industrial processing facilities
- Conduits/pipes

Application Requirements

Habitats

- Pressure containment
- Atmosphere composition/control
- Thermal control (active/passive)
- Acoustic control
- Radiation protection
- Meteoroid protection
- Integrated/natural lighting
- Local waste management/recycling
- Airlocks with scrub areas
- Emergency systems
- Psychological/social factors

Storage Facilities/Shelters

- Refrigeration/insulation/cryogenic systems
- Pressurization/atmospheric control
- Thermal control (active/passive)
- Radiation protection
- Meteoroid protection
- Hazardous material containment
- Maintenance equipment/tools

Supporting Infrastructure

- All of the above
- Regenerative life support (physical/chemical and biological)
- Industrial waste management

Types of Structures

Habitats

- Landed self-contained structures
- Rigid modules (prefabricated/*in situ*)
- Inflatable modules/membranes (prefabricated/*in situ*)
- Tunneling/coring
- Exploited caverns

Storage Facilities/Shelters

- Open tensile (tents/awning)
- "Tinker toy"
- Modules (rigid/inflatable)
- Trenches/underground
- Ceramic/masonry (arches/tubes)
- Mobile
- Shells

Supporting Infrastructure

- Slabs (melts/compaction/additives)
- Trusses/frames
- All of the above

Material Considerations

Habitats

- Shelf life/life cycle
- Resistance to space environment (uv/thermal/radiation/abrasion/vacuum)
- Resistance to fatigue (acoustic and machine vibration/pressurization/thermal)
- Resistance to acute stresses (launch loads/pressurization/impact)
- Resistance to penetration (meteoroids/mechanical impacts)
- Biological/chemical inertness
- Reparability (process/materials)

Operational Suitability/Economy

- Availability (lunar/planetary sources)
- Ease of production and use (labor/equipment/power/automation and robotics)
- Versatility (materials and related processes/equipment)
- Radiation/thermal shielding characteristics
- Meteoroid/debris shielding characteristics
- Acoustic properties
- Launch weight/compactability (Earth sources)
- Transmission of visible light
- Pressurization leak resistance (permeability/bonding)
- Thermal and electrical properties (conductivity/specific heat)

Safety

- Process operations (chemical/heat)
- Flammability/smoke/explosive potential
- Outgassing
- Toxicity

Structures Technology Drivers

Mission/Application Influences

- Mission objectives and size
- Specific site-related conditions (resources/terrain features)
- Site preparation requirements (excavation/infrastructure)
- Available equipment/tools (construction/maintenance)
- Surface transportation/infrastructure
- Crew size/specialization
- Available power
- Priority given to use of lunar material & material processing
- Evolutionary growth/reconfiguration requirements
- Resupply versus reuse strategies

General planning/design considerations

- Automation and robotics
- EVA time for assembly
- Ease and safety of assembly (handling/connections)
- Optimization of teleoperated/automated systems
- Influences of reduced gravity (anchorage/excavation/traction)
- Quality control and validation
- Reliability/risk analysis
- Optimization of *in situ* materials utilization
- Maintenance procedures/requirements
- Cost/availability of materials
- Flexibility for reconfiguration/expansion
- Utility interfaces (lines/structures)
- Emergency procedures/equipment
- Logistics (delivery of equipment/materials)
- Evolutionary system upgrades/changeouts
- Tribology

Requirement Definition/Evaluation

Requirement/Option Studies

- Identify site implications (lunar soil/geologic models)
- Identify mission-driven requirements (function and purpose/staging of structures)
- Identify conceptual options (site preparation/construction)
- Identify evaluation criteria (costs/equipment/labor)
- Identify architectural program (human environmental needs)

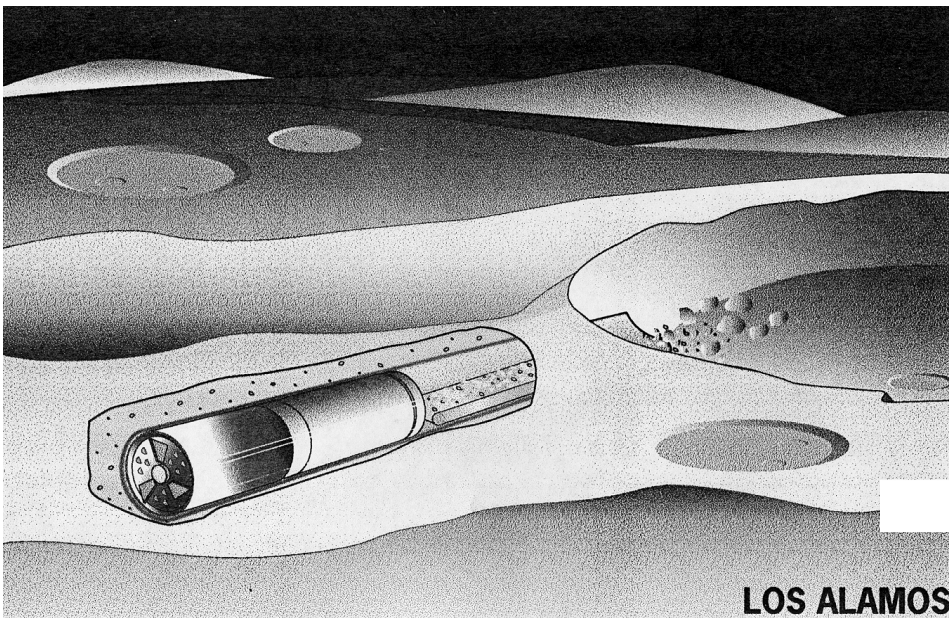
Evaluation Studies

- Technology development requirements
- Cost/benefit models (early/long-term)
- System design optimization/analysis

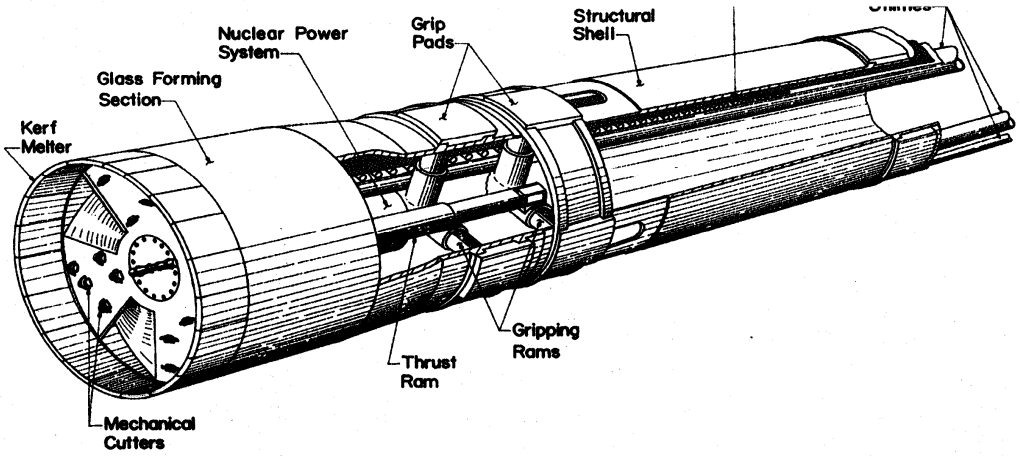
Construction of Planetary Habitation Tunnels Using a Rock-Melt-Kerfing Tunnel-Boring Machine Powered by a Bimodal Heat Pipe Reactor

J. D. Blacic, M. G. Houts, *Los Alamos National Laboratory*
T. M. Blacic, *University of California at Davis*

Planetary Tunnel Concept



Tunnel Borer Concept (Rock melt kerfing for tunnel support)



Lunar Kerf-Melting TBM

	Tunnel Diameter		
	2m	3m	5m
Thermal Power, kW	245	365	604
Habitat Volume Produced per day, m^3	25	56	157

Assumptions:

- Advance rate — 8 m/d
- Thickness of glass structural lining — 5 cm
- Regolith bulk density — 2000 kg/m^3
- Glass density —3300 kg/m^3
- Regolith melting temperature — 1150°C
- Specific heat — 1 kJ/kg K
- Latent heat of fusion — 420 kJ/kg

200 kWt/5 kWe HPS Point Design

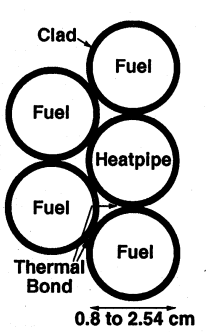
❖ UN Fueled reactor (passive shutdown)	250 kg
♦ Nb-1Zr or Mo heatpipes, Na or Li working fluid	
❖ Shield	50 kg
♦ Reduce radiation dose to sensitive components	
❖ Thermoelectric power conversion	85 kg
❖ Instrumentation and control	50 kg
❖ Power Conditioning	20 kg
❖ Cabling	30 kg
Total	*485 kg*

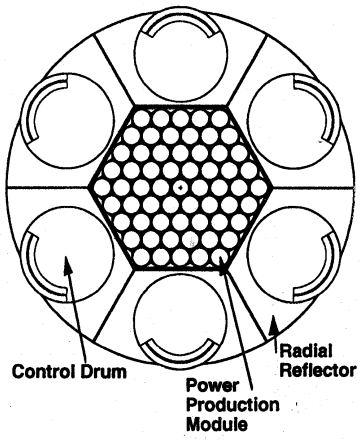
Additional Features

- ❖ TBM can be steered by asymmetric heating using manipulation of reactor control drums.
- ❖ Excess heat (after electrical conversion) removed by heating conveyed rubble or by providing coprocess heat
- ❖ Residual thermal cooling cracks in glass lining sealed by plasma spraying an indigenous metal (e.g., Fe, Al, etc.)
- ❖ After habitat building, TBM parked with kerf melters exposed to space — provides electrical power to habitat for ~10 years.

HPS: One Potential Power Source

- ❖ Couples well to rock-melt-kerfing TBM
- ❖ Several point designs have been investigated.
  - ♦ System mass (5 kWe/10 year life) less than 600 kg
  - ♦ System mass (50 kWe/10 year life) less than 2000 kg
  - ♦ Potential for development cost <$100 M, unit cost <$20 M
    - ♦ Modules contain 2 to 6 fuel pins and one heatpipe.
    - ♦ Heat conducts from fuel to primary heatpipe.
    - ♦ Primary heatpipe transfers heat to secondary heatpipe and/or power converters.
    - ♦ Temperature to power converters > 1275 K.





Habitat Construction Requirements

Marvin E. Criswell and Jenine E. Abarbanel
Center for Engineering Infrastructure & Sciences in Space and Department of Civil Engineering
Colorado State University, Fort Collins, Colorado

Introduction

Demand	≤	Supply
Loads, forces	Satisfy with acceptable	Resistance
Requirements	reliability and economy	Solutions

Conditions on the Moon and Mars (similar but different)

- Less than 1% of Earth's atmosphere
- 17% and 38% of Earth's gravity
- Dusty, rocky regolith surfaces
- Wide temperature ranges

Overall Goal: Mission Economy

Less Costs	↔	Less transportation cost	↔	Less mass to import
Net imported mass savings	=	Reduction	–	Increase

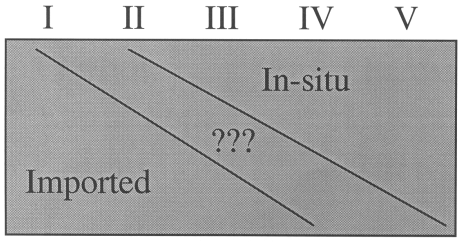
Less imported end product

Replace x kg of imported product with y kg of *in situ* (usually y>x)

More imported systems
- mining, transporting
- processing, refining
- manufacturing
- fabrication
- humans, robotics
- life support
- power

Question: What is feasible and economical? When?
First step: What is possible?

	Habitat needs	depend on	Base Maturity
	Feasible uses	depend greatly on	Base Maturity
	(Sadeh, Criswell)	(Eckart)	(IAA Lunar Base Group)
I	Exploratory	Prepatory/Exploratory	Temporary Outpost
II	Pioneering	Research Outpost	Permanent Outpost
III	Outpost	Operational Base	Full Lunar Base
IV	Settlement	Extended Base	Factory
V	Colony	Self-sufficient colony	Settlement



← To judge the need and feasibility of *in situ* material use, must identify base maturity assumed

Changes in Habitat Needs with Base Maturity

- Some requirements are basic for human life — always there (changes are in size, magnitude, volume)
  - Shelter
  - Internal atmosphere
  - Food, water
  - Temperature control
  - Other needs for humans to survive and thrive
- Others depend on base/habitat maturity (stage)
  - Expanded mission and role
  - More use of plants for food, other biological systems
  - Facility becomes more "permanent"
  - Crew stays become longer

Opportunities and Practical Uses of In Situ Materials

- Opportunities — increase greatly with base maturity
  - More resources (human, energy, equipment)
  - More synergism with base "commercial" products
  - More incentives to "close loops" for self-sufficiency
  - More knowledge about local resources
  - More time to acquire and use technology and equipment
- What uses are feasible, economic?
  - Very dependent on maturity of
    - Base, habitat
    - Enabling technologies
    - Base site and mission

Comment: A use may not be economic at the given stage, but may have a payoff for the long term.

Categories of In Situ Material Use

- In-place habitat structure
  - Structural shell, shielding, fixture, facilities
- Habitat interior life support contents
  - Artificial atmosphere, water, environmental systems
- Closely associated base infrastructure
  - Pathways, roadways, landing/launchpads, human-occupied manufacturing and commerce areas
- Energy and other habitat support systems
  - Electric power, heat management, plant growth, and other food systems
- Construction equipment

Requirements — Basic Habitat Structures

- Structurally contain 10–14.7 psi (70-100 kPa) internal pressure
  - Human occupied habitats are pressure vessels!
  - Basic structure must be strong in tension
- Provide shielding — radiation, micrometeorites, thermal stability
  - Passive system of mass shielding
  - Less downward gravity force from shielding than upward from pressure
- Provide high reliability, damage control, durability, low leakage
  - Design, materials, fabrication all involved
- Support habitat/base functions; adequate size, shape
  - Functional planning and architecture
  - Compatible with outfitting, operations
- Stay open and retain basic form if depressurized (planned, unplanned)
  - Hard/Rigidized/Frame
- Facilitate access to "outside," other base facilities
  - Air locks (personnel, supplies); interface to rovers; dust control; minimum air loss

Uses of In Situ Materials — Basic Habitat Structure

- Pressure vessel: Imported rigid or membrane tensile structure
  - Later → *in situ* for secondary interior structure; abrasion, insulating, other layers of shell
    Still later → glass, metal, post-tensioned concrete, cermaics, etc. for primary structure
- Shielding: Regolith (loose, bagged, otherwise contained)
  - Blocks of concrete, masonry, ice arch or igloo
  - Boxes of sintered basalt, etc. filled with regolith
- Interior walls, floor, furnishings
  - Early structural use within habitat?
  - Continue to import high value products, such as hinges, screws
- Foundations, anchors
  - Minimize and simplify through design
  - Existing and upgraded regolith for fill and foundations
  - Screw anchors into suitable regolith/geology
  - Tension line plus anchor mass — low *g*, high friction

Requirements: Habitat Interior, Life Support

- Artificial atmosphere:
  - Pressure
  - Mix of gases:
    - Oxygen for human needs
    - CO_2 for plants
    - Low enough O_2 for fire safety

Comments: O_2 is 21% of Earth's atmosphere

- Large volume × low density = large mass, a lot to import
- Leakage = loss of mass = $$$
- Water: Human consumption, other operations, sanitation
- Food
- Other life support and waste resource recycling systems
- Special needs to support base mission/operations

Use of In Situ Resources — Inside Habitat, Nonstructural

- Atmospheric Gases

Availability	Human Needs			Plant Needs
		Buffer Gasses		
	Oxygen	Argon	Nitrogen	Carbon Dioxide
Moon	Oxides/Water	?	?	?
Mars (thin atmosphere)	0.13% O_2	1.2%	3%	95%

Note: Oxygen is less than 1/3 of artificial atmosphere mass. Source of other needed gases on the Moon TBD.

- Water
  - From oxides
  - From water deposits (where? how much? how easy to get?)
  - Byproduct/coproduct with fuel generation and other products

Closely Associated Infrastructure

Needs	*In situ* material use
❖ Transportation infrastructure Paths and roadways ♦ Concerns: Trafficability; dust maintenance want hard, smooth surface	❖ Use coarser fraction of regolith for gravel roads ♦ place over imported or locally produced textiles
❖ Launch/landing areas ♦ Concerns: Blast and dust control. Need hard surface to minimize dust pickup; berms to direct the blast.	❖ Early use for concrete, sintered basalt ceramic, etc. ❖ Paving blocks
❖ Tanks, boxes, containers	❖ Simple, not glamorous
❖ Other human-occupied areas (see habitats)	❖ Need; too "simple" to import. Early use of marginally structural materials? High pressure tanks later.

Energy and Other Habitat Support Systems

Needs	*In Situ* Material Use
❖ Energy generation	
♦ Solar cells	♦ *In situ* derived cells?
♦ Supporting structure	♦ Metals, glass, ceramics?
♦ Wiring, piping	♦ Metals in basic shapes?
❖ Energy management	
♦ Electric energy storage (including for night time use)	♦ ?? EEs — help
♦ Insulation	♦ Regolith granular materials? Ceramic foam? Fiber glass?
♦ Heat energy storage or dissipation	♦ Granular regolith "heat sink" plus heat pump, heat pipes?
❖ Plant growth systems	♦ Regolith-derived soils

Construction Equipment and Operations

❖ Imported Construction Equipment	
♦ Problem — want small mass to import, but need mass for friction, stability	Imported equipment made with carbon and other composites. Design so some members, containers can be filled with regolith
❖ Tie downs, mining, excavation equipment, etc.	
❖ Equipment for more mature base	Combine imported components with frames, booms, buckets — made of local metals?

Summary

- ❖ Habitat material-related requirements depend on base maturity
- ❖ Opportunities & feasibility of *in situ* material use depends greatly on base maturity (also its size and mission).
  - ♦ Thus, identify proposed *in situ* material use with base maturity and mission
- ❖ Savings in imported mass through the use of *in situ* materials must consider "investment in mass" needed to gather, process, fabricate, etc.
  - ♦ Thus, big technical challenges in miniaturizing processes
- ❖ Habitats are pressure vessels containing gases having significant mass. Also provided — shielding, thermal stability.
- ❖ Many requirements/needs in areas of secondary structures, surfaces, containers — other "routine, nonglamorous" areas
- ❖ Appropriate mix of high value imported and locally available/produced will constantly change.

SEMICONDUCTORS: *IN SITU* PROCESSING OF PHOTOVOLTAIC DEVICES

Peter A. Curreri
Space Science Laboratory, NASA Marshall Space Flight Center

Lunar PV Cells

- Silicon options
  - Bulk crystal
  - Thin films (Landis 90)
    - Polycrystalline thin films
    - Amorphous thin films
- Design for Vacuum
  - Back contact cells (Sinton & Swanson 90)
  - Laser cut junction isolation (Micheels & Valdivia 90)
  - Ion implantation (Bentini et al. 82)
- Vacuum Processing
  - Thin films (Landis 89)
  - Metals extraction (Fang 88)
  - Resources extraction (Curreri 93)

Key Challenges

- Growth production facilities using *in situ* materials and minimal import (Earth "smarts" vs. mass)
- Use solar power for extraction and fabrication
- Design power systems, production facilities, extraction facilities for:
  - Maximum production from *in situ* materials
  - Maximum use of solar power
  - Minimum import from Earth

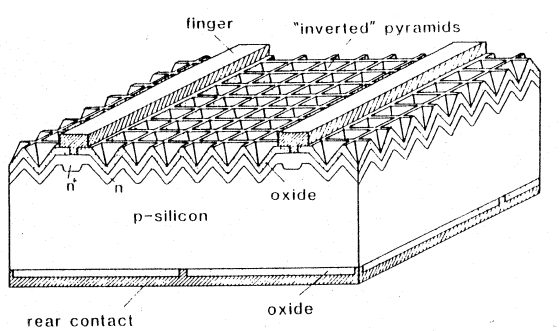


Fig. 1. Schematic diagram of the passivated emitter and rear cell (PERC cell).

Fabrication of Large Photovoltaic Arrays in Space from Lunar Materials

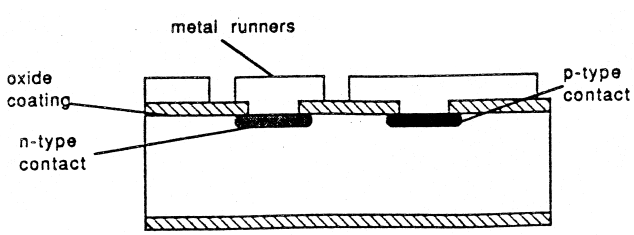


Fig. 2. A cross-sectional diagram of a point-contract solar cell.

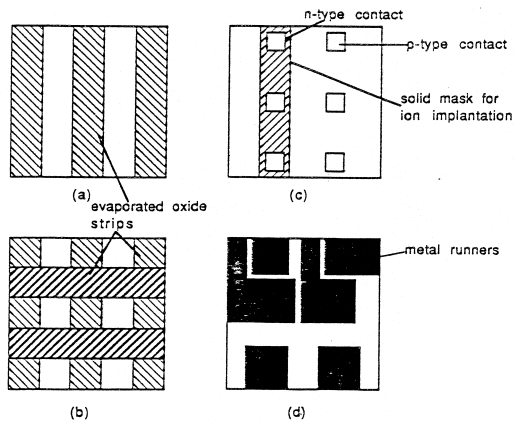


Fig. 3. Fabricating point-contact solar cells in space. (a) Evaporated oxide strips on silicon. (b) Crossing oxide strips forming point contacts to silicon. (c) Solid masking used to ion implant n- and p-type contacts. (d) Metal runners for electrical contact to silicon.

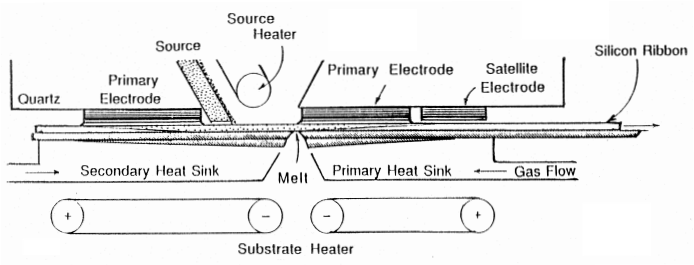


Fig. 4. Schematic of the growth apparatus.

Opportunities for ISRU Applications in the Mars Reference Mission

Michael B. Duke
Lunar and Planetary Institute, Houston, Texas

Objectives of Presentation

- Consider whether ISRU other than propellants/life support consumables can be useful to the Reference Mission
- Outline the type of analysis that has to be performed to evaluate the benefits of ISRU use
- Suggest some areas for investigation

Question

- Can use of indigenous planetary materials reduce the cost or risk of the reference mission?

Ways to Reduce Cost

- Offset the need to transport mass from Earth to Mars
- Increase the duty cycle or capacity or system lifetime of operating systems
- Reduce crewtime requirements for operations, maintenance, etc.

Ways to Reduce Risk

- Increase robustness of infrastructure
- Mitigate environmental hazards
- Reduce risk of accident or malfunction

Strategies

- Preplacement of assets with robotic systems
- Crew enhancements to surface systems

Characteristics of Robotic Preplacement Strategies

- Reduce total system mass by producing over a long period of time
- The mass of the robotic production system must be a fraction of the mass of the materiel that would have to be transported to Mars to provide the same function
- Actions that are simple and repetitive will be most effective

Example — Create Pressurizable Volume

- Benefits and Reduced Risks
  - Offsets requirement to transport mass to Mars for living and working areas, including plant-growth facilities
  - Allows more efficient volumetric transportation modes for internal systems brought from Earth
  - Allows economical expansion from initial base
  - Provides for ground-level or below-ground facilities to reduce radiation risk
- Costs and Increased Risks
  - Complex production system
  - Additional assembly tasks for crew
  - Technical risks associated with airlock designs
  - Unfamiliar technology

Concrete Structures

- Assume that all materials for concrete and rebar are available, including water
- Approximately 10 metric tons of the reference mission's Mars surface habitat is associated with structures — structure is 7.5 m diameter × 7.5 m high, with two floors
- Assume that all floors and walls are constructed of reinforced concrete, 25 cm thick. Total amount of concrete required: $52m^3$ – 104 T
- If produced in 1 yr, this requires production of 280 kg of concrete/day - ~30 kg/hr for a 10 hr day
- If that amount of reinforced concrete can be produced, mixed, formed, cured, etc. with 1–2 T of robotic equipment, concrete may be able to compete with Earth supply

Other Possibilities

- Concrete or sintered blocks for roadways and pads
  - Reduce dust dispersion
  - Increase traverse speed/reduce power required
  - Move large objects
- Sintered regolith for radiation shielding
  - Reduce radiation hazard
  - Simplify hab module design
- Concrete for unpressurized structures
  - Protection of pressurized, unpressurized rovers from radiation, thermal cycling, dust reduces maintenance requirements

Example — Road-Grading

- Road grading can be done robotically
  - Can be performed with a 200 kg robotic system (which is able to add rock or soil ballast for additional weight)
  - Rover assumed to be able to prepare 1 m of roadway in 10 min
  - Production of 1.5 km of roadway requires 15,000 min
- Road assumed to allow traversal at 15 km/hr instead of 3 km/hr
- Transportation required between two habitat modules located 1.5 km apart, twice a day for two people
  - Road saves 40 min of traverse time daily for 500 day mission, or 20,000 minutes (60,000 minutes for three mission strategy)
  - Saves crew time
  - Could use same rover, modified for crew transport

Conclusions

- Use of ISRU in the construction of Reference Mission infrastructure is more complex than bringing things from Earth.
- Because many activities can be done robotically over long periods of time, the daily production/ accomplishment rate can be quite low, consistent with capabilities of low-mass systems.
- More detailed studies could provide savings for the Reference Mission and build capability for expansion beyond an initial outpost.

Materials Transportation

H. A. Franklin
Bechtel Technology Inc., San Francisco

Move Materials, Cargo

- Forklifts
- Loaders
- Telescopic handlers
- Skid steers
- Cranes
- Conveyor belts

Move Dirt and Rocks

- Bucket excavators
- Bulldozers
- Scraper earthmovers
- Trenchers
- Backhoes
- Skid steers
- Conveyors and pipelines

Typical Skid Steer Data

- Operate through doorways and in confined spaces
- Versatile, adaptable tool modules
- Payload capacity: 900 to 1800 lbs
- Vehicle weight (1*g*): 3000 to 6000 lbs
- Power required: 30 to 60 HP (22 to 45 KW)
- Equivalent area PV cells: up to 5500 sq. feet

Typical Large Earthmovers

- Dedicated to hauling large volumes on rough mining roads
- Payloads: 120 to 340 tons
- Vehicle weight (1*g*): 230 to 435 tons
- Power required: 1200 to 2500 HP (900 to 1900 KW)
- Equiv. area PV cells: up to 227,000 sq.ft.

Road Services

- Reduce damage to terrain
- Reduce stress, damage to vehicles
- Reduce dust to facilities
- Reduce navigation demands
- ISRU applications
  - Concrete, basalt, etc. pavers
  - Glass, concrete poles for drag grading

Heatpipe Power System (HPS) and Heatpipe Bimodal System (HBS)

Michael G. Houts, David I. Poston, and Marc V. Berte
Los Alamos National Laboratory and Massachusetts Institute of Technology

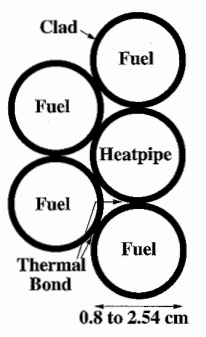
Assumptions behind the HBS and HPS

- Space fission systems can enhance or enable potential missions of interest:
  - Advanced exploration of moon and Mars.
  - Advanced deep space missions.
  - Defense missions.
  - Commercial missions.
- Space fission systems will only be used if they are safe, have adequate performance, and can be developed within reasonable cost and schedule. Cost and schedule will be drivers.

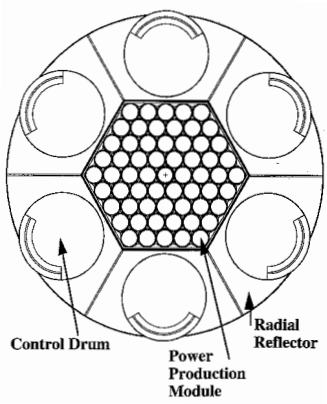
Goal is to develop an approach that will allow space fission systems to be utilized.

HPS: One approach to power-only systems.

- All desired system attributes for ensuring utilization.
- Several point designs have been investigated.
  - System mass (5 kWe/10 year life) less than 600 kg (unicouple TE).
  - System mass (50 kWe/10 year life) less than 2000 kg (unicouple TE).
  - Potential for development cost < $100 M, unit cost < $20 M.



- Modules contain 2 to 6 fuel pins and one heatpipe.
- Heat conducts from fuel to primary heatpipe.
- Primary heatpipe transfers heat to secondary heatpipe and /or converters.
- Temperature to power converters >1275 K.



HPS: Why Low Cost?

- Passive safety. Safety verified by zero-power criticals.
- Simple system, few system integration issues.
- Full power electrically-heated test of flight unit.
- Flight qualification with electrically-heated tests and zero-power criticals. No ground nuclear power test unless requested by sponsor.
- Fuel and core materials operate within database, even for multi-decade missions. No nuclear-related development required.
- No pumped coolant loop or associated components.
- Assured shutdown without in-core shutdown rod.
- Most issues resolved by electrically-heated module tests.
- Can be built with existing U.S. technology. Russian technology can enhance performance; international cooperation may be cost effective.
- Multiple fuel and power-conversion options.

HPS: Why Low Mass?

- Higher core fuel fraction than other concepts:
  - Reduces reactor volume/mass
  - Reduces shield volume/mass
- Simple:
  - No hermetically sealed vessel / flowing loops
  - No EM pumps
  - No lithium thaw system
  - No gas separators
  - No in-core shutdown rods
  - No auxiliary coolant loop
  - Simplified system integration

HPS 5 kWe "Off-the-Shelf" Design

- UN Fueled Reactor (passive shutdown) 250 kg
  - Nb-1Zr / Na heatpipes
- Shield 100 kg
  - 2 m dose plane at 10 m, 1013 nvt/5 × 10^5 rad in 10 yr
- Thermoelectric Power Conversion 85 kg
- Instrumentation and Control 50 kg
- Power Conditioning 20 kg
- Boom/cabling 70 kg

Total 575 kg

HPS Power Options

	HPS7N HPS7O/SA HBS10O	HPS7O	HPS12O/SA	HPS12O
TE	6 kWe	12 kSe	36 kWe	60 kWe
AMTEC	16 kWe	32 kWe	96 kWe	160 kWe
CBC	25 kWe	50 kWe	150 kWe	250 kWe

Rated thermal power assuming worst-case single heatpipe failure.
Mass of core, reflector, control drums, and primary heat transport: HPS7N = 240 kg; HPS7O = 325 kg; HPS10O = 370 kg; HPS12O=480 kg.
Mass of power conversion, shield and other components not included.

HPS/HBS Safety

- Virtually non-radioactive at launch (no plutonium)
- Passive removal of decal heat
- High radial reflector worth eases design for launch accident subcriticality
- Passive launch accident subcriticality (current baseline) can be ensured by using liners or structures that contain absorbers (rhenium or other)
- If desired, launch accident subcriticality can also be ensured by any one of the following methods
  - Launch shutdown rod
  - Removal of some fuel from the core during launch
  - Removable boron wires placed in interstitials

HPS Module Test Accomplishments

- Utilized existing test apparatus and heaters to reduce cost and schedule
- Demonstrated that high power (4 kWt) can be conducted into a 2.54-cm-diameter heatpipe operating at >1300 K and transported to the condenser against gravity
- Demonstrated adequate heatpipe performance at >1300 K with peaks (corresponding to fuel pin bonds) in evaporator radial heat flux
- Demonstrated that module thermal and mechanical bonds have adequate resistance to thermal stresses, thermal cycling, and other loads
- Demonstrated advanced refractory metal bonding and machining techniques
- Module fabrication/initial tests const <$75 K

Summary of Module Tests Performed to Date

Parameter	Value
Peak operating power (transported to condenser-end)	4.0 kWt
Peak heatpipe operating temperature (during module test)	>1400 K
Peak heatpipe operating temperature (during module fabrication)	>1500 K
Number of module startups (frozen to >1300 K and/or >2.5 kWt)	9

HPS / HBS Development Status

- Neutronic and thermal performance verified for numerous point designs
- Mass and lifetime estimates made for numerous point designs
- HPS module fabrication complete, module tests successful
- Conceptual design of HBS module. HBS module, heatpipe, and heaters under fabrication. Full-power test planned for 1998.

Next Step

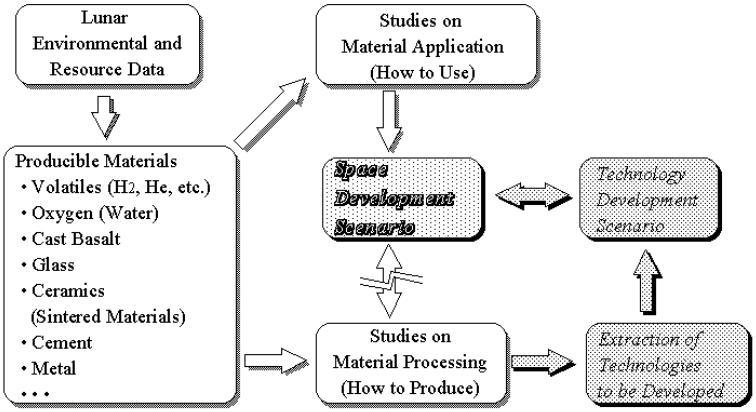
- Fabricate HPS or HBS core and demonstrate system thermal hydraulics using resistance heaters to simulate nuclear fuel. Evaluate normal and off-normal operation, plus startup.
  - Superalloy system < $0.5M
  - Refractory metal system $1.0M
  - Option to add power conversion subsystem at modest cost
  - First full thermal-hydraulic demonstration of US space fission system since 1960s
- Use core to demonstrate nuclear properties
  - Add fuel, reflector, and control system
  - Perform zero-power criticals at LANL, SNL, or elsewhere

Goal: Get something flying!

Considerations on the Technologies for Lunar Resource Utilization

Hiroshi Kanamori
Shimizu Corporation, Space Systems Division

Resource Utilization Studies



Evolutional Scenario of Lunar Base

		Developmental Phase				
		I Survey	II Outpost	III Initial	IV Expand	V Autonomous
Crew Size		0	4	5	8	15 <
Mission Period		< 14 days	45 days	90 days	180 days	Permanent
Electrical Power	(day)	< 1 kW	20 kW	40 kW	120 kW	200 kW <
	(night)		9 kW	15 kW	45 kW	90 kW <
Number of Habitats			1	1	1	2 <
Number of Laboratories			0	0	2	4 <

Candidates for Lunar Products

Products	Components	Process examples	Lunar Base Phases I	II	III	IV	V
Oxygen	O_2	Reduction, Electrolysis, etc.	·····	·····	→	→	→
Non-Processed Regolith	Regolith, Bags	Digging, Banking, Bagging, Piling	·····	·····	→	→	→
Cast Basalt and Glass	Silicates	Gradual or Rapid Cooling of Molten Basalt	·····	·····	→	→	→
Ceramics	Al_2O_3, MgO SiO_2, etc.	Sintering Regolith		·····	→	→	→
Cement	CaO, Al_2O_3, SiO_2, etc.	Sintering and Crushing Anorthite			·····	→	→
Metals	Fe, Ti, Si, Al, Mg, etc.	Reduction and/or Electrolysis			·····	→	→

Technologies to be Studied for Lunar Resource Utilization

		Gas Desorption	Oxygen		Non-processed Regolith		Cast Basalt & Glass		Ceramics		Cement		Metals		Composites	
			Initial	Advanced	Initial	Advanced	Initial	Advanced	Initial	Advanced	Initial	Advanced	Initial	Advanced	Initial	Advanced
Infrastructure	Excavation, Mining															
	Surface Transportation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Energy															
Preliminary Processing	Beneficiation	●		●			●		●	●	●	●	●	●	●	●
	Heating and Cooling Control	●	●	●		●	●	●	●	●	●	●	●	●	●	●
	Reduction		●	●						●	●	●	●	●	●	●
	Electrolysis		●	●							●	●	●	●	●	●
	Melting and Solidifying					●	●				●	●	●	●	●	●
	Sintering							●	●	●		●	●	●	●	●
Secondary Processing	Refining and Purifying						●		●			●	●	●	●	●
	Concrete (Mixing, etc.)									●						●
	Assembling (Welding, etc.)					●	●	●	●	●	●	●	●	●	●	●

Infrastructure Technologies

- Excavation, Mining
  - > Drill, Core (include Sampling)
  - > Scrape, Scoop, Shovel
  - > Cave, Blast

- Surface Transportation
  - > Conveyor, Cart, Truck

- Energy
  - > Generation
  - > Transmission
  - > Storage

Preliminary Processing

- Beneficiation
  - > Sizing (Screen, etc.)
  - > Electrostatic Separation
  - > Magnetic Separation

- Heating and Cooling Control
  - > ~1000 K (Gas Desorption)
  - > ~1500 K (Sintering)
  - > ~2000 K (Melting, Smelting)
  - > ~3000 K (Pyrolysis)
  - > ~10000 K (Plasma)

Preliminary Processing (2)

• Reduction	> H_2, C, CH_4, F, HF, Al, Li, Na, etc.

• Electrolysis	> ~ 373 K (Liquid Water)
	> ~ 1000 K (Vapor Water)
	> ~ 1000 K (Molten Salts w/ Flux)
	> ~ 1700 K (Molten Silicates)

Preliminary Processsing (3)

• Melting and Solidifying	> Casting
	> Other Forming (Spinning, etc.)
	> Finishing (Fine Form)
	> Tempering

• Sintering	> Powder Production and Mixing
	> Forming
	> Sintering
	> Tempering

Secondary Processing

• Refining, Purifying	> Gas Purification
	> High Grade Glass and Ceramics
	> Pure Metal

• Concreting	> Mixing, Forming
	> Curing

• Assembling	> Jointing
	> Welding

Materials Refining for Structural Elements from Lunar Resources

Geoffrey A. Landis
Ohio Aerospace Institute, NASA Lewis Reseearch Center

Use of *in situ* resources for construction on the Moon will require manufacturing structural materials out of lunar resources. Likely materials that could be manufactured from lunar materials include steel, titanium, aluminum, and glass (for glass-fiber composite). Process sequences for manufacturing these materials out of lunar regolith are discussed.

Lunar Structural Materials

Low availability on the Moon:

- Graphite fiber; SiC fiber; artificial fiber composites (Kevlar, Spectra, etc.)
  - Used as advanced lightweight structural materials on Earth, but low availability of carbon on the Moon makes these poor choices.
- Polymer-matrix composites (epoxy; polyester)
  - Low availability of carbon on the Moon makes these poor choices
- Cement, concrete
  - Common paving and building material on Earth, but low availability of water on the Moon makes these poor choices.
- Asphalt
  - Common paving material on Earth, but low availability of carbon on the Moon makes this a poor choice

Available on the Moon:

- Metals
  - Steel
    - Common terrestrial structural material; many variant compositions
  - Aluminum
    - Common terrestrial structural material
  - Titanium
    - Uncommon terrestrial material; used where extremely light weight is required; high temperature makes it difficult to work with
- Composites
  - Glass/glass composite
- Paving/construction materials
  - Sintered-regolith brick
  - Glass-matrix regolith brick

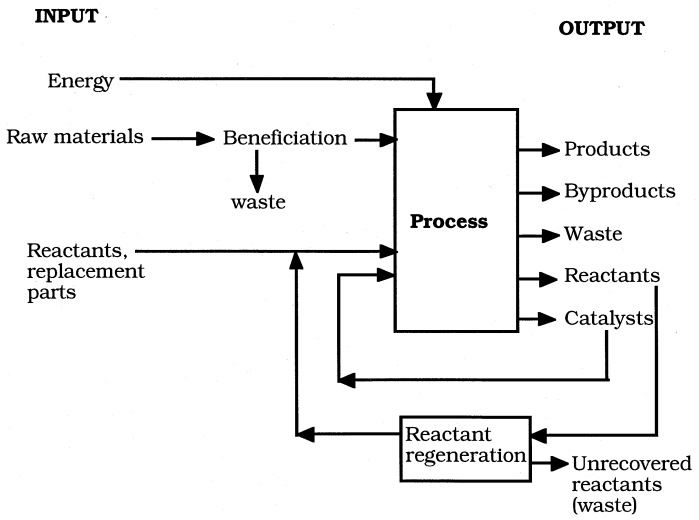


Fig. 1. Generic flow chart for material processing.

Process Selection Criteria

- Make as many useful materials as possible
- Minimize input from Earth
  - 100% recycling of non-lunar reactants (slag must not bind reactant or catalyst)
  - Minimum replacement parts need (crucibles require many batches without replacement avoid sacrificial electrodes)
- Minimize energy requirements
- Avoid high temperature process steps where possible
- Subject to other constraints, chose simplest possible process

Steel Production from Meteoritic Iron

- A few tenths of a percent of the regolith may consist of metallic nickle-iron deposited in the from of micrometeorites
- Separate from soil using magnets may require grinding soil first
- Product will be iron/nickel alloy typical of meteorites
- Minimum energy requirements
- Probably the easiest structural material to refine

Alternate process: refine iron from lunar regolith

- More complicated and energy-intensive process
- Same process as refining aluminum
- May be byproduct of silicon manufacture

Glassmaking for Composites

- A glass/glass composite requires two components; fibers and matrix
- Bulk glass is excellent in compression; poor in tension
- Glass fiber is excellent in tension
- Glass/glass composites have good strength in both tension and compression

Proposed composite: Anorthite fibers in aluminosilicate matrix

Part 1: Fibers

- Anorthite fiber — Anorthite (calcium aluminosilicate) is purified from the lunar plagioclase, then melted to make glass. The melting point of anorthited, approximately 1550°C, is relatively high, making it difficult to work with. Mackenzie and Claridge suggest addition of calcium oxide, to form a composition of roughly 46% CaO, 42% SiO_2, 11% Al_2O_3, and 1% trace, to reduce the melting point to 1350°C. Purity of starting materials is not critical unless transparency is needed.
  - Simple two-step process
    - beneficiate to pure anorthite
    - melt and draw into fibers
  - Moderate energy requirements (1350°–1550°C)
  - Requires some prospecting to locate best ore
  - Requires refined calcium oxide to lower melt temperature
- Alternative: Fused silica fiber — the low thermal expansion coefficient of pure silica is a disadvantage, since it is desirable for the matrix material to have a lower thermal expansion coefficient than the fiber.
  - Well-developed technology
  - High temperature process (1710°C)
    - Corrosive
    - Needs high temperature crucibles
    - Energy intensive
  - Requires refined silicon oxide
  - Other components can be added to lower melt temperature

Part 2: Matrix

The matrix must consist of a material with a significantly lower melting temperature than the fibers.

Aluminosilicate glass

- Typical composition:

SiO_2	57%
Al_2O_3	20%
MgO_3	12%
CaO	5%
B_2O_3	4%
Na_2O	1%
trace oxides	1%

  - Major constituents are common on the Moon.
  - Minor constituents are less common, but available.
  - Melt temperature (ca 1130°C) is 200–400° below melt of anorthosite, so this can be used as a matrix.
  - Melt temperature will below melt temperature of regolith, so this could be used as a matrix for sintered regolith bricks.
  - Melt temperature and thermal expansion coefficient can be modified by changing composition.
- More complicated process; requires refined input materials.
- Modest energy requirements (1140°C) plus energy required for refining
- Requires refining Na and B; elements of low abundance on the Moon
  - Prospecting may be desirable, to find pyroclastic deposits enriched in these materials.
  - Deleting Na and B from formula will increase melt temperature slightly; this change may be worth making if Na or B is difficult to refine.
  - If there is lage-scale refining of lunar material for other purposes (i.e., producing silicon for solar cells), Na and B will be produced as an un-used byproduct. In this case it may be desirable to add more NaO and B_2O_3, to decrease melt temperature.

Aluminum Production

Aluminum is likely to be a byproduct of silicon production. Aluminum production processes include electrolysis processes and fluorine reduction.

Terrestrial aluminum production require sacrificial electrodes and uses nonrecycled cryolite; not applicable to the Moon. Modified electrolysis techniques are possible.

For silicon production on the Moon, see (1) Landis G., "Materials Refining for Solar Array Production on the Moon," presented at the Workshop on Space Resource Utilization, Lunar and Planetary Institute, Houston TX, Dec. 11–12, 1998, and (2) "Solar Array Production on the Moon," SPS-97: Space and Electric Power for Humanity, Aug. 24–28, 1997, Montreal, Canada, pp. 311–318.

Aluminum produced during silicon production (same process also refines glass precursors)

- Fluorine brought to the Moon in the form of potassium-fluoride/sodium fluoride/calcium fluoride salt mixture
- Potassium fluoride electrolyzed from eutectic salt to form free fluorine and metallic potassium; temperature: 676°C
- Fluorine reacted with heated lunar regolith to form SiF4, oxygen, and metal fluorides; temperature: 500°C
- Gaseous SiF_4 and TiF_4 separated from oxygen by condensation; 178°K
- SiF_4 reacted in plasma to form silicon and recover fluorine reactant; 300°C
- Potassium metal added to metal fluorides to produce metallic aluminum and iron; temperature: 500°C
- Oxygen added to mixture of potassium metal with calcium fluoride to recover potassium fluoride and calcium oxide; temperature: 520°C