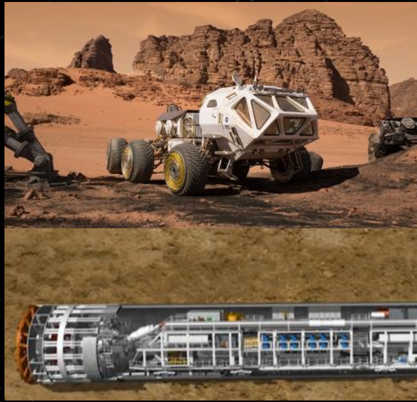
Challenges and Opportunities for Using Tunnel Boring Machines (TBM) to Develop Underground Structures on the Moon



By:
Jamal Rostami, PhD, PE
Haddon, Alacer Gold Endowed Chair
Professor, Dept. of Mining Engineering,
Director Earth Mechanics Institute (EMI),

Christopher B. Dreyer, Ph.D.
Professor of Space Resources
Space Resources Program
Associate Director of Engineering,
Center for Space Resources,

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Brad R Blair
CTO, MoonRise Inc.

moonrise

Lunar Surface Innovation CONSORTIUM

Administered by the JOHNS HOPKINS APPLIED PHYSICS LABORATORY

July 30th, 2021

Image courtesy of SKIDMORE, OWINGS & MERRILL LLP

I would like to **leave** you with following thoughts

* We need to establish a base on the moon, for habitation, and infrastructure for deep space activities.
* The base cannot be at surface due to adverse conditions
  → has to be underground
* It is not feasible to use Cut and Cover tunneling
  → the tunnel as to be mined
* Conventional tunneling is not suitable for Space / Lunar construction
  → Use TBMs

Image courtesy of SKIDMORE, OWINGS & MERRILL LLP

Excavation engineering and Earth Mechanics Institute (EMI) has been one of the leading institutions in rock drilling and excavation

EXCAVATION ENGINEERING & EARTH MECHANICS INSTITUTE

CSM has graduate programs with MS and PhD Degrees in:

- **Underground Construction and Tunneling (UTC) – the only degreed program in the US**

underground

- **Space Resource Engineering (SRE) – first one in the world**

Center for Space Resources

COLORADO SCHOOL OF MINES

EARTH • ENERGY • ENVIRONMENT

SOM, ESA & MIT Partnership
Moon Village Architecture

MOON VILLAGE
SKIDMORE, OWINGS & MERRILL LLP, THE EUROPEAN SPACE AGENCY & MIT ACADEMIA

https://www.som.com/news/som_releases_concept_for_moon_village_the_first_permanent_human_settlement_on_the_lunar_surface

Moon's surface is inhospitable, difficulties

- Vacuum
- Radiation
- Extreme Temperatures (-180 to 120˚) gradients
- Low Gravity, 1/6th of Earth
- Potential for impact by meteorites
- No cooling or flushing medium
- Dust suspension over extended time
- Limited source of power
- Difficulty in Repair/Maintenance
- Cost of $100k+/lb for sending material to moon
- No humidity

Conclusion:
Base Cannot be at the surface

Moon’s surface is inhospitable, difficulties

Primary impact:

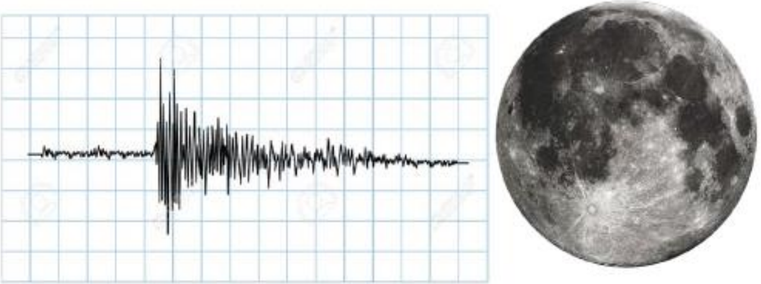
Source: Antonio Bobet, Purdu Univ.
ARMA 2019 Keynote speech

Direct damage

- Meteorites impact moon surface on a regular basis since there is no atmosphere to burn them ,

Secondary impact:

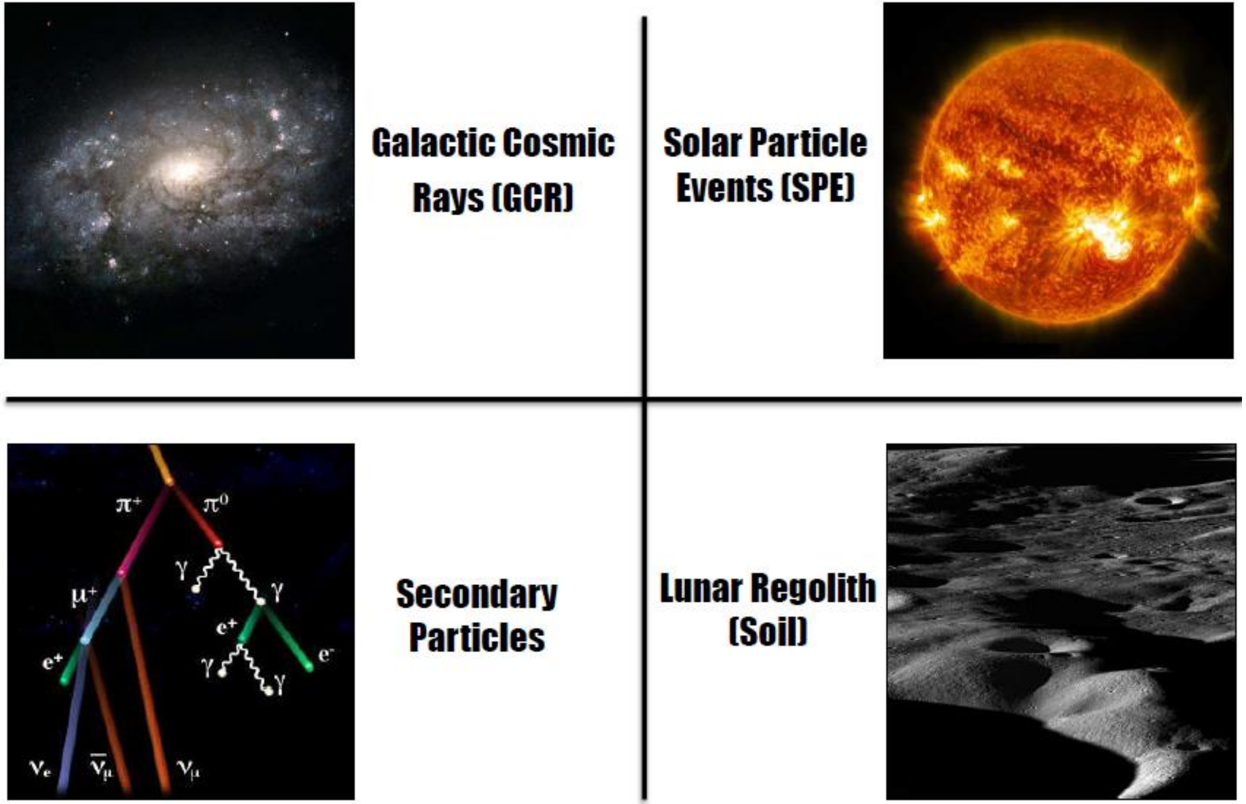
Ejected particles



Seismic activity

Moon’s surface is inhospitable, difficulties

- Radiation, various sources

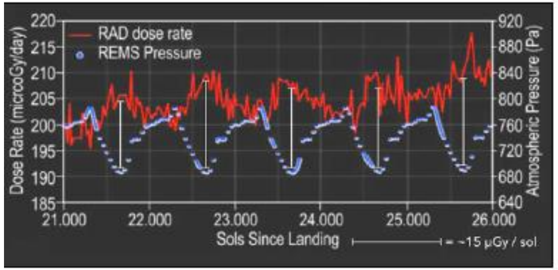


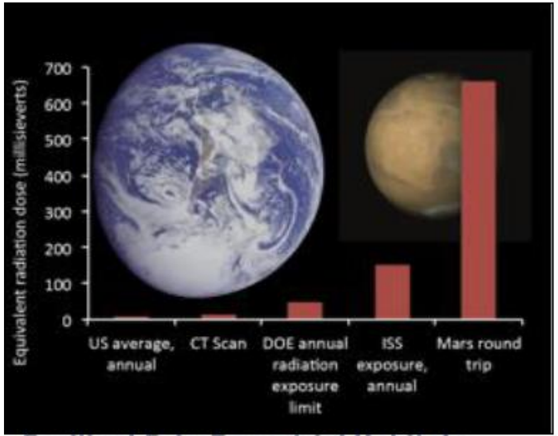
Source: Antonio Bobet, Purdu Univ.
ARMA 2019 Keynote speech

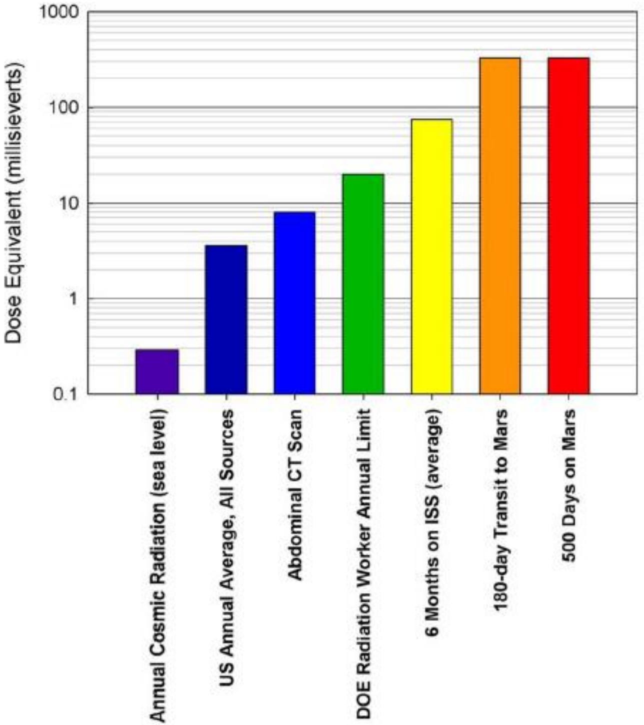
Moon's surface is inhospitable, difficulties

MSL carried the first ever dosimeter for both the cruise to Mars and surface exposure

- Radiation, various sources







Source: Antonio Bobet, Purdu Univ.
ARMA 2019 Keynote speech

Launch Pads, Construction sites

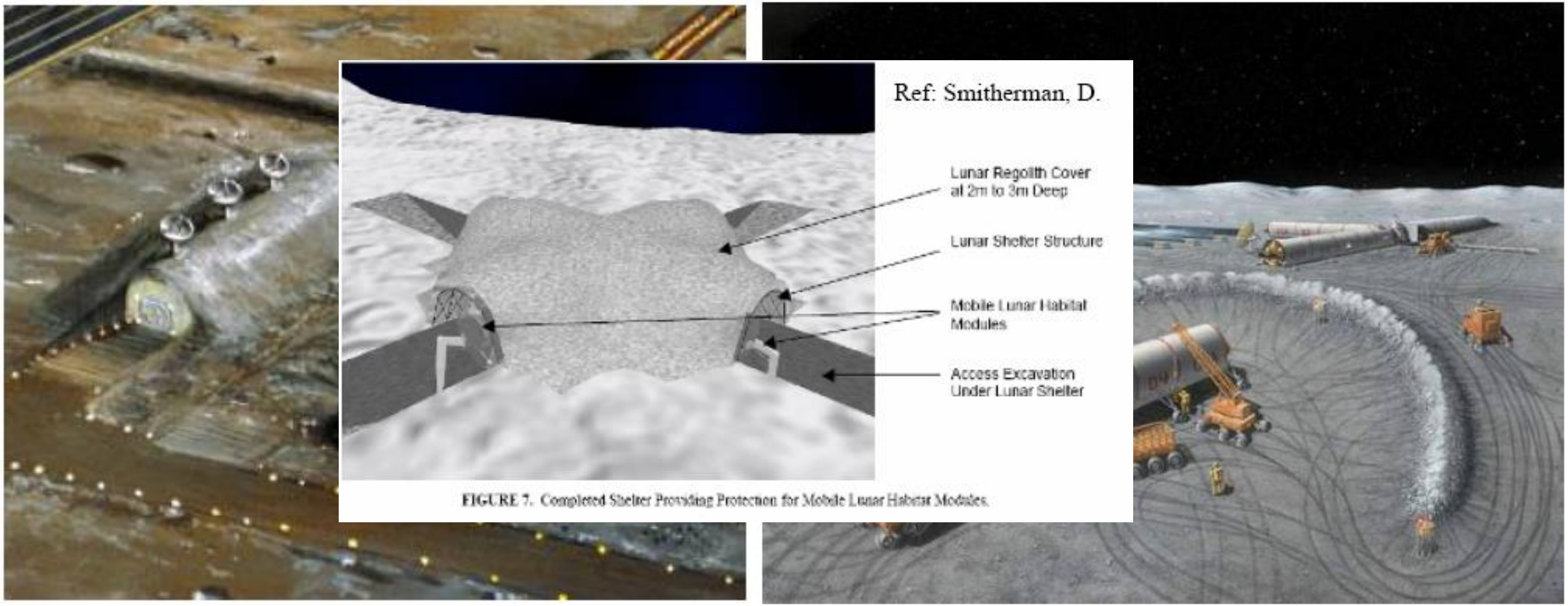
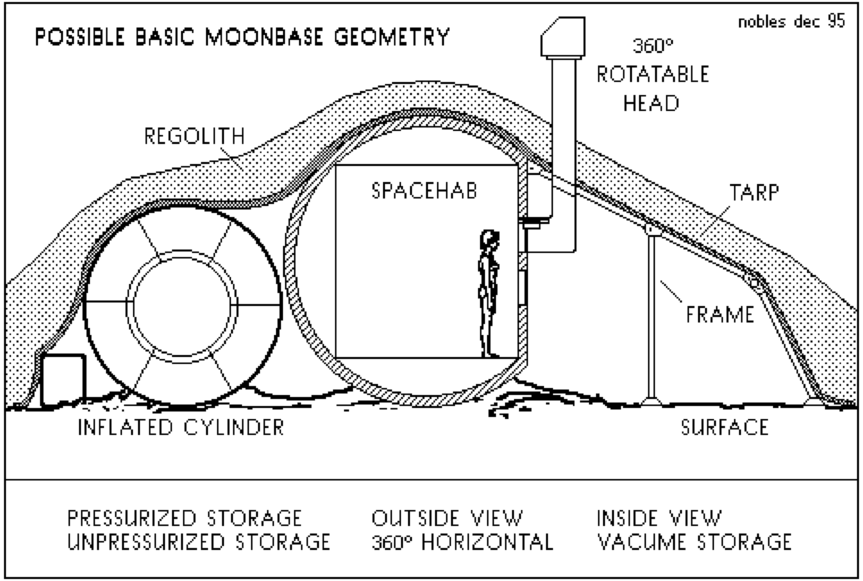


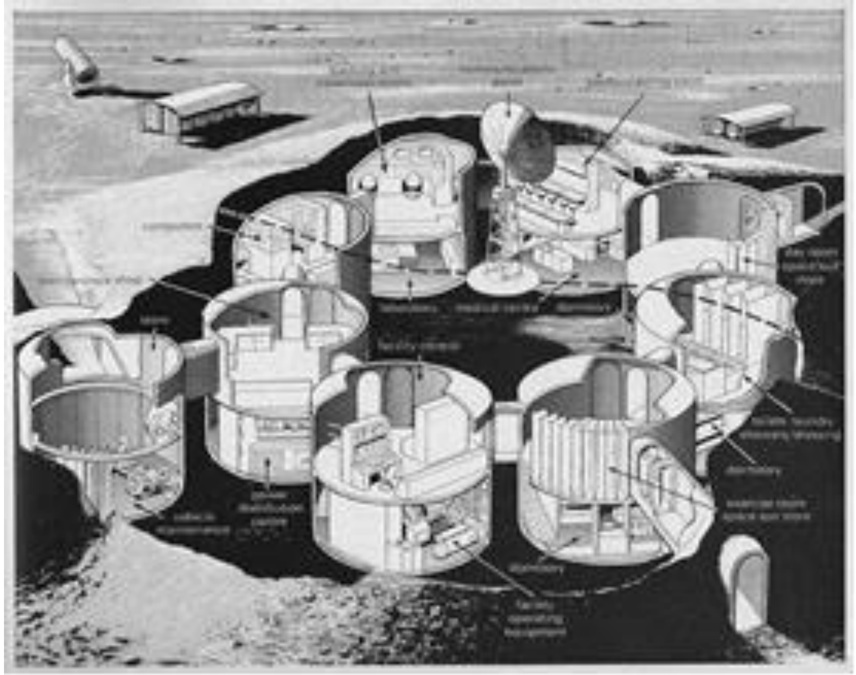
FIGURE 7. Completed Shelter Providing Protection for Mobile Lunar Habitat Modules.

Robert P. Mueller: rob.mueller@nasa.gov

Underground Space is Critical to Survival

- Concepts of buried Habitats





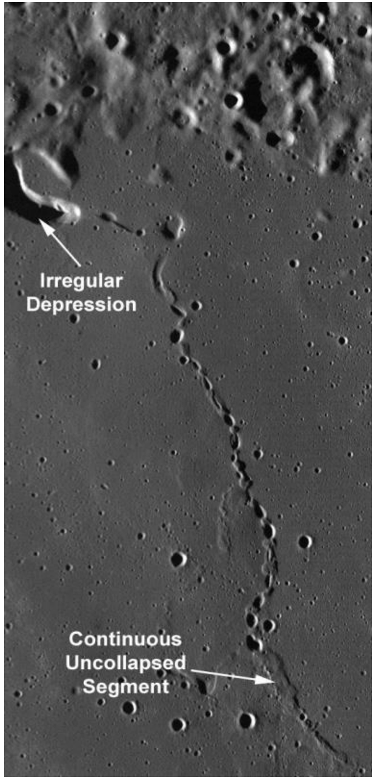
Application to Human Habitats

- Long term habitation of the lunar bases is enabled by underground spaces for living, farming, storage, plants, . . . to avoid:
  - Surface Radiation
  - Excessive Temperatures
  - Impact by meteorites
  - Maintaining pressure/atmosphere
- Connection of spaces using tunnel boring units

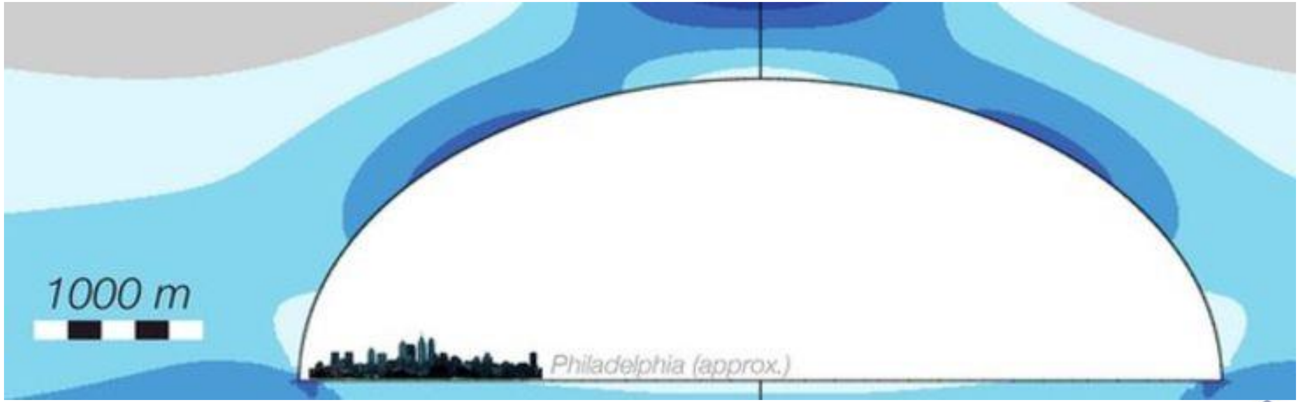
Davis Meltzer illustration in National Geographic School Bulletin, May 5, 1969

Opportunities, Lava Tubes

- Access to lava tubes
  - Tunnel into side of stable tube
  - Avoid the collapsed sky lights
  - Future location of a human habitat

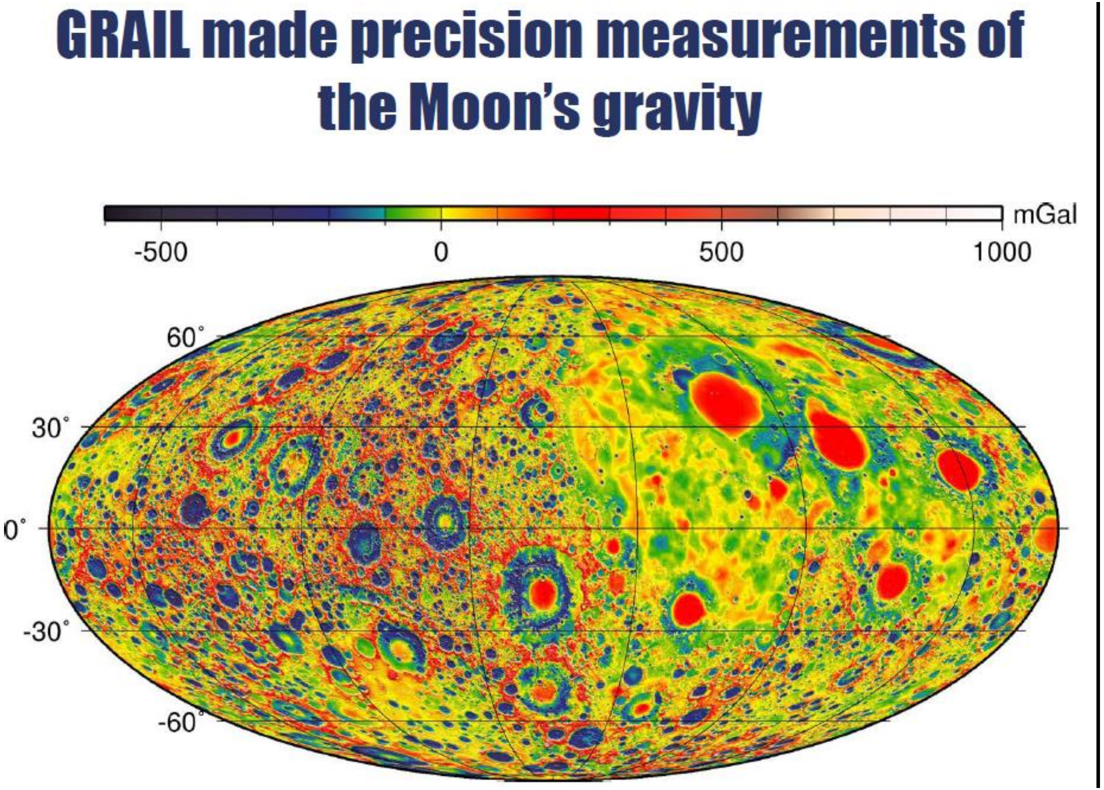


A 40 km long and 500 m wide lava tube with collapsed and intact sections. https://photojournal.jpl.nasa.gov/catalog/PIA14010



Opportunities, Lava Tubes

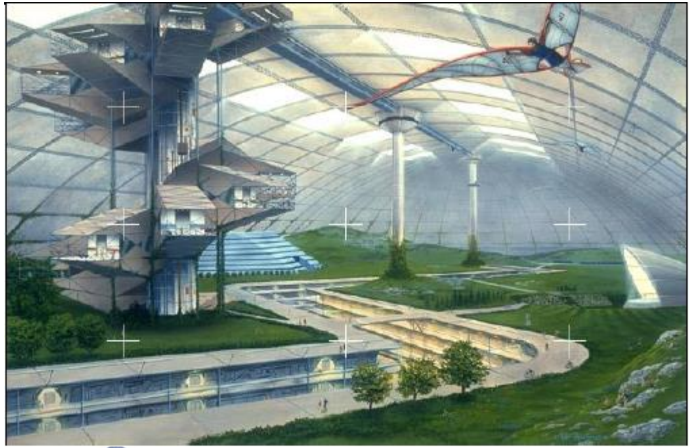
- Low gravity shows potential location of the Lave Tubes



Source: Antonio Bobet, Purdu Univ.
ARMA 2019 Keynote speech

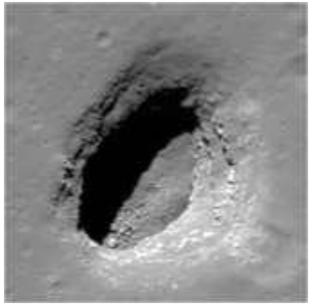
Opportunities, Lava Tubes

- Lava tubes are ideal for astronaut habitats, offering safety from radiation, temperature changes, micrometeorites and even dust

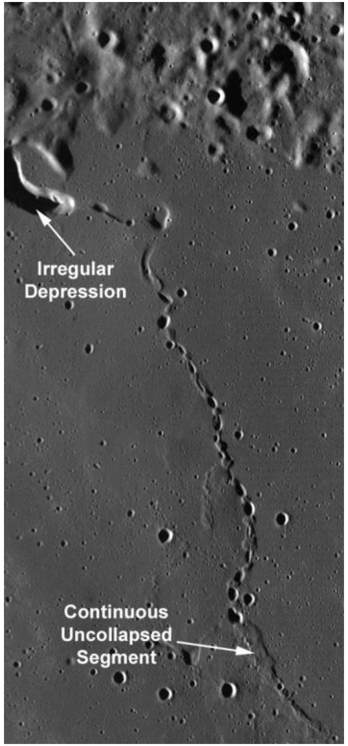


Exploration

- Access to lava tubes
  - Tunnel into side of stable tube
  - Avoid the collapsed sky lights
  - Future location of a human habitat



Mare Ingenii Skylight



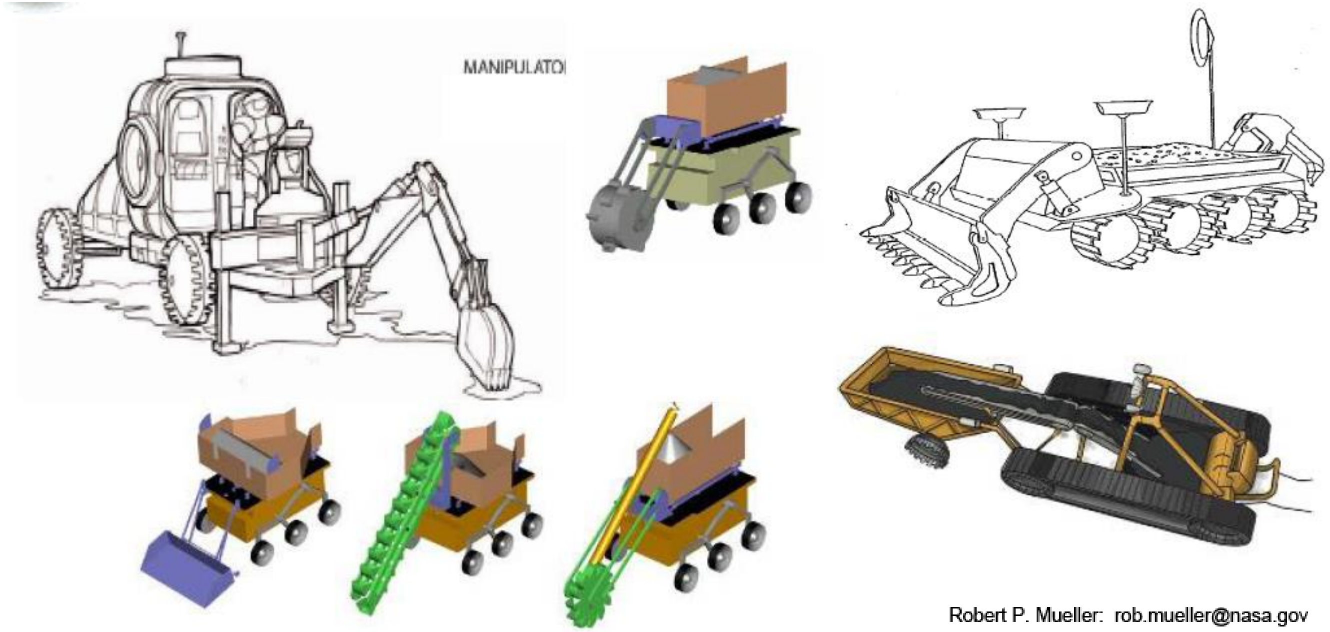
A 40 km long and 500 m wide lava tube with collapsed and intact sections. https://photojournal.jpl.nasa.gov/catalog/PIA14010

The challenges of

Excavating on the moon,

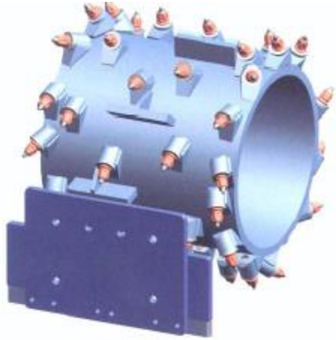
Image courtesy of SKIDMORE, OWINGS & MERRILL LLP

Excavation on the moon

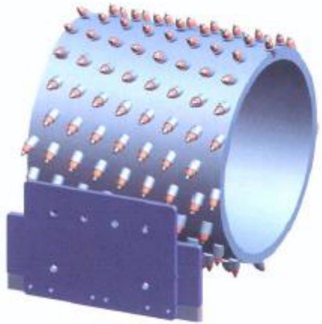


- None is suitable for excavating compacted or frozen soil or rock

Roadmilling Machine



FCS milling drum and scraper
with 500 mm working width



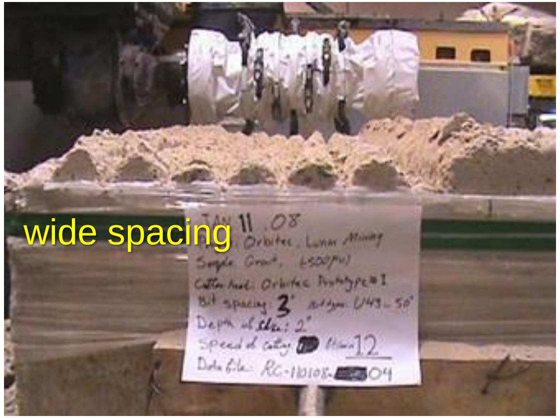
FCS fine milling drum and scraper
with 500 mm working width

FCS milling drum and scraper
with 400 mm working width

FCS milling drum and scraper
with 300 mm working width

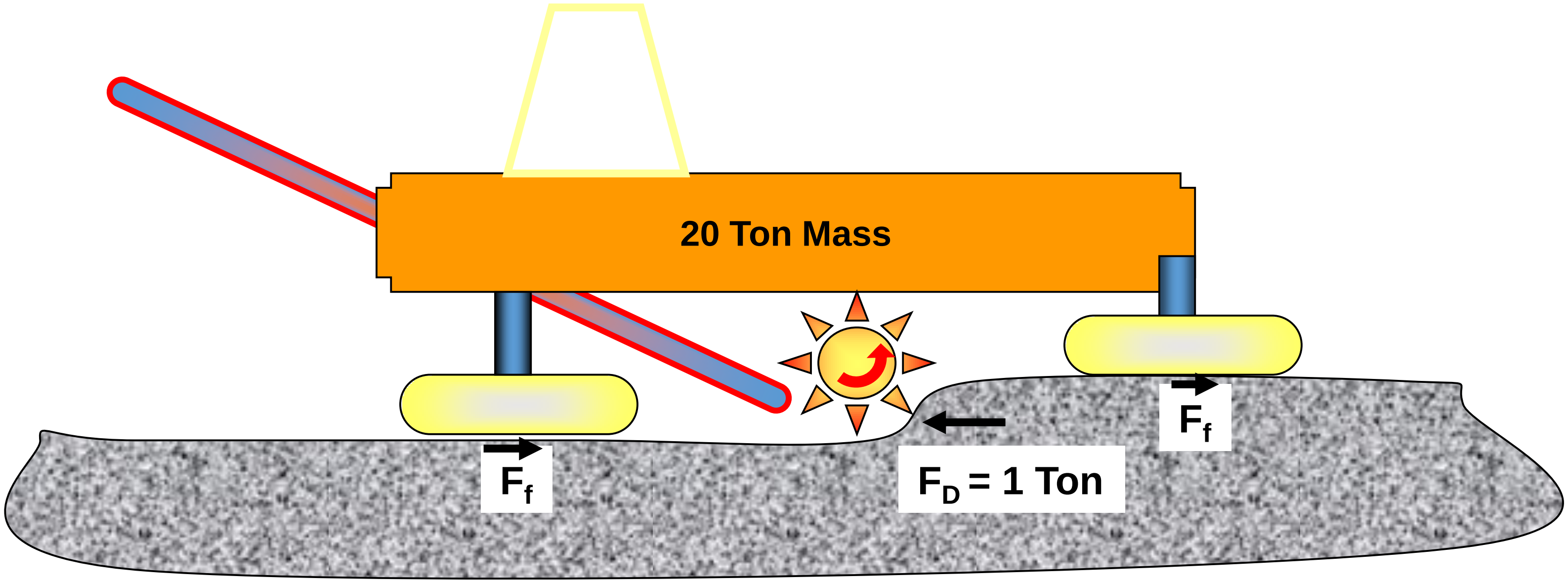
Excavatability Testing: Rotary Cutting

- Full-sized cutterhead
  - Variable spacing w/o changing bits
- Test parameters
  - Rotation rate 60 rpm
  - Forward speeds 0.3-7.6 m/min
  - Depths of cut 13-64 mm
  - Cut spacings 25-76 mm
- Simulant materials cut
  - Limestone ≈ 10% ice in regolith
  - Stronger sand grout ≈ 2.4% ice
  - Weaker sand grout ≈ 0.9% ice



Static Balance of Forces

- Machine has to load itself first to gain sufficient mass to react to required forces

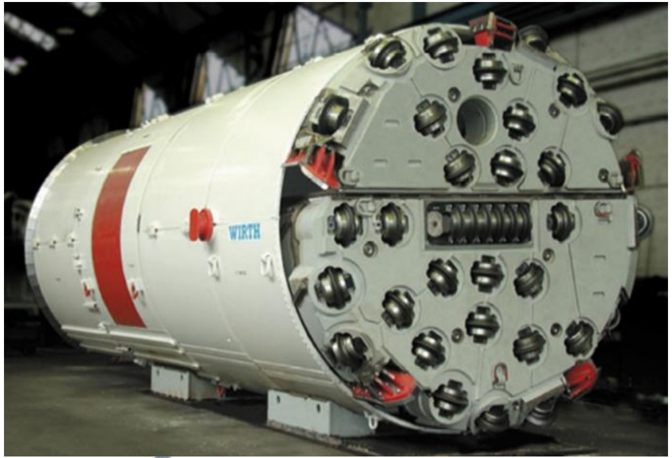


Tunneling practice

Cut & Cover →

←Conventional

Mechanized (TBM) →

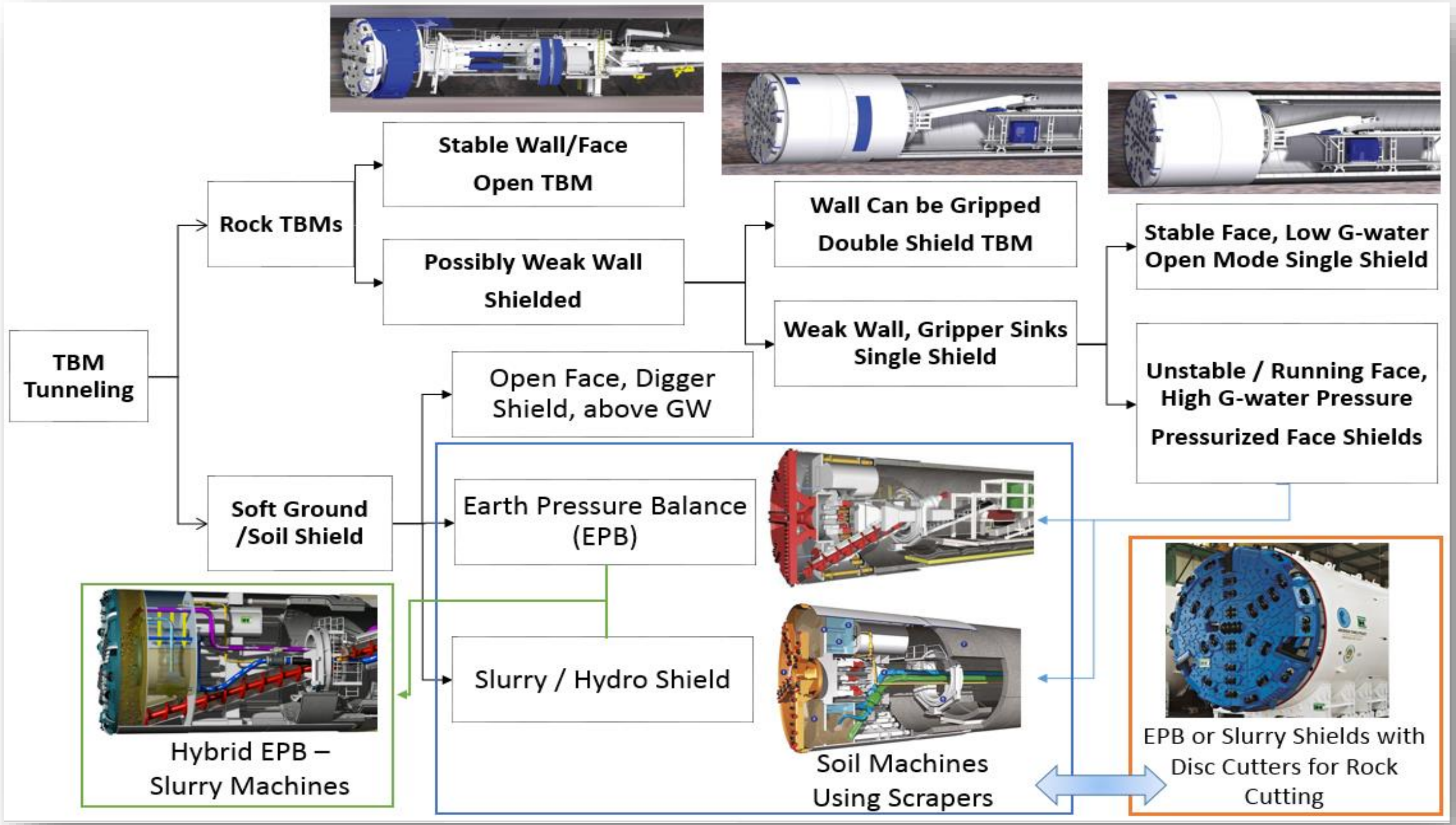


Advantages of TBM

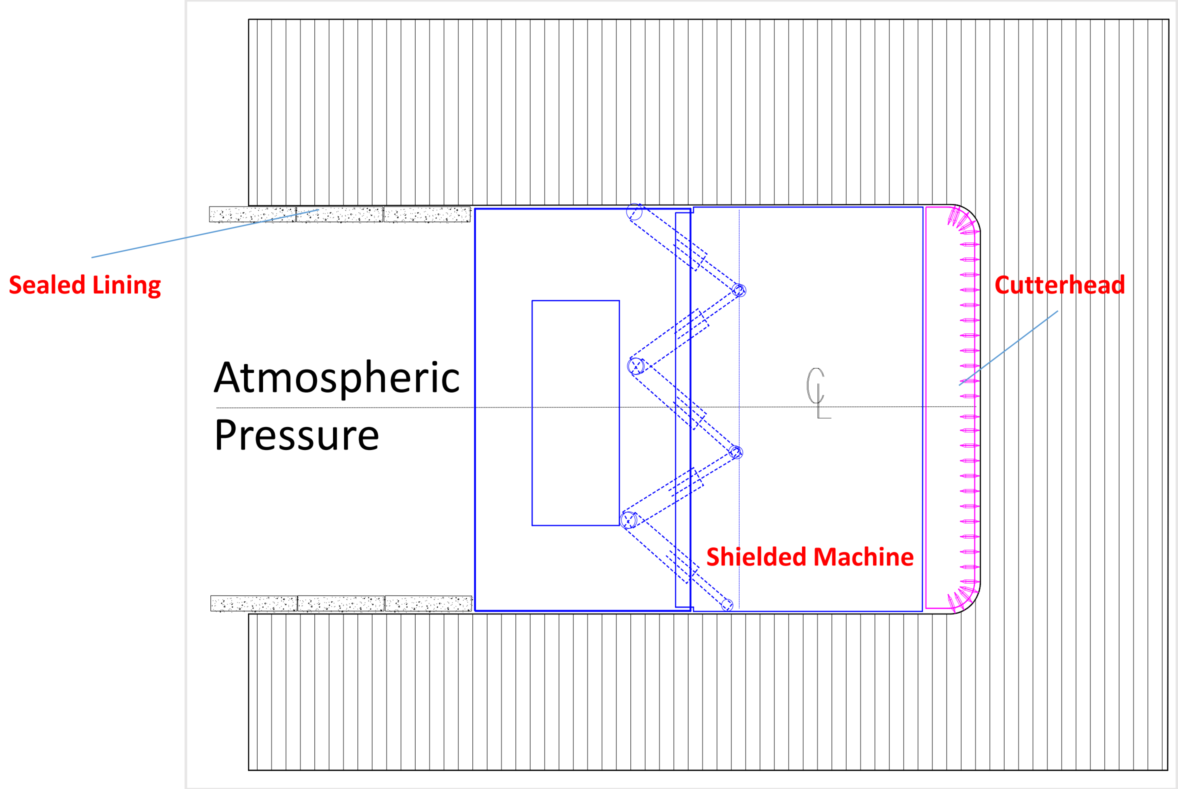
- Machines are self contained and can generate the excavation forces/torque by gripping on the walls, or pushing against installed lining
- Can be automated
- Can install a shell/lining that is sealed to operate under atmospheric pressures

- Requires small crew
- Can cut through various materials including soil, frozen regolith, rock,
- Relatively well understood technology
- Machines are versatile and robust

TBM Types


TBM Tunneling
Rock TBMs
Stable Wall/Face
Open TBM
Possibly Weak Wall
Shielded
Wall Can be Gripped
Double Shield TBM
Weak Wall, Gripper Sinks
Single Shield
Stable Face, Low G-water
Open Mode Single Shield
Unstable / Running Face,
High G-water Pressure
Pressurized Face Shields
Open Face, Digger
Shield, above GW
Soft Ground
/Soil Shield
Earth Pressure Balance
(EPB)
Slurry / Hydro Shield
Soil Machines
Using Scrapers
Hybrid EPB –
Slurry Machines
EPB or Slurry Shields with
Disc Cutters for Rock
Cutting

Shielded machines operating under high differential pressures



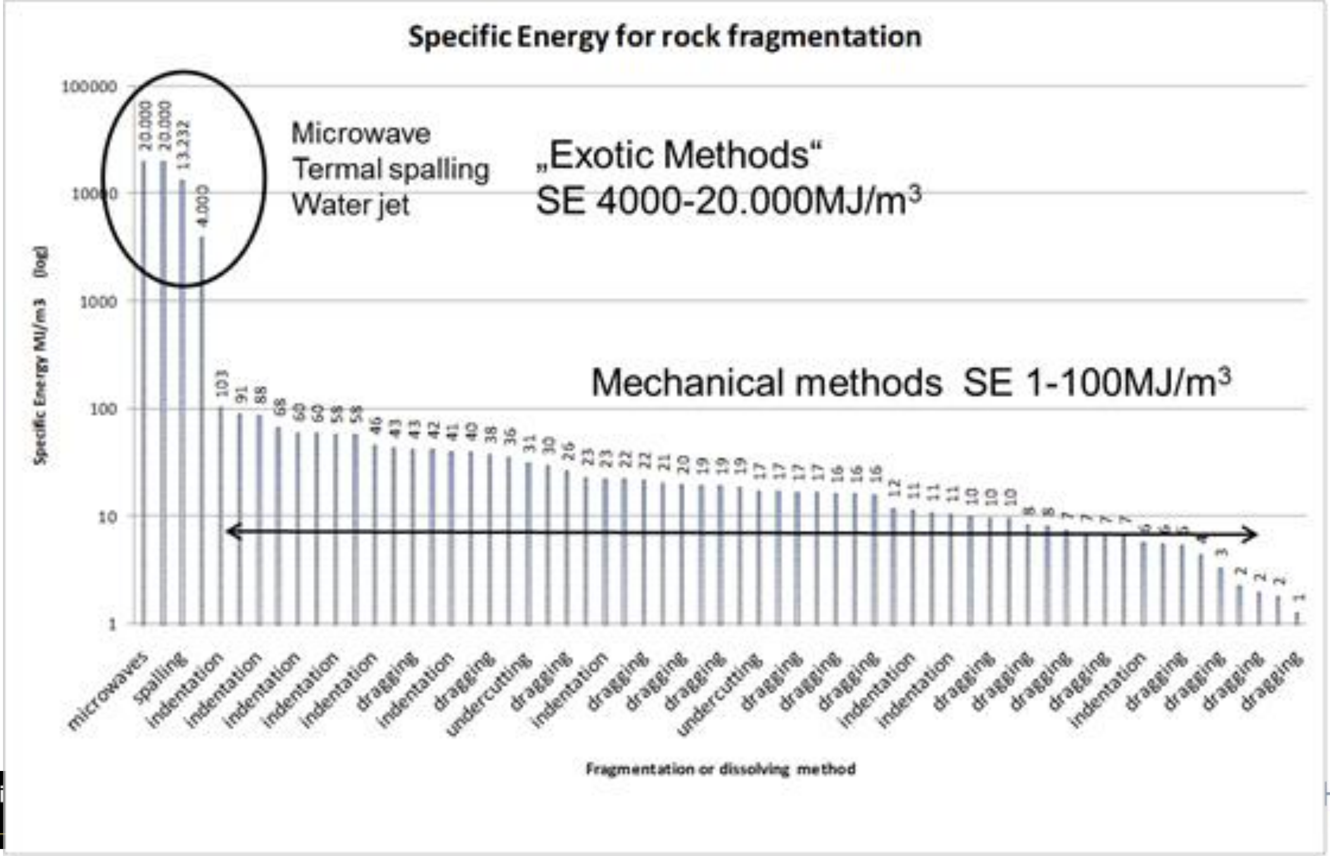
Example of Elevated Pressure up to 17 bar on Earth

Typical Challenges in TBM Operation

- Machi
- Site m
- Muck
- Adver
- Open
  - Ba
- Doubl
  - Fa
  - Sq
- Excessive wat
- Release of gases (methane, H2S, etc)

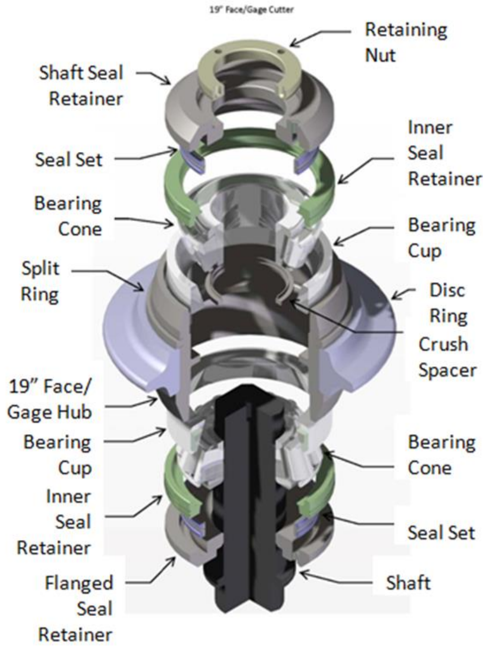
Challenges for the Lunar TBM - Cutting

How to Excavate the material



Challenges for the Lunar TBM - Weight

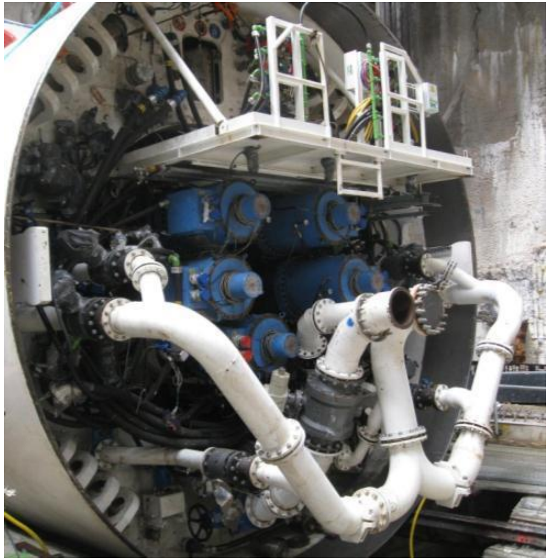
- A typical TBM with back up system weights a few hundred tons
- Cutters and machine components are typically steel and heavy
- Potential Solutions
  - Redesign and use different materials to reduce the weight
  - Recycle parts /repair onsite
  - Manufacture TBM parts in place from lunar materials, such as the structure



Face/Gage Cutter Assembly

Challenges for the Lunar TBM - Power

- A typical TBM uses several hundreds kW electrical
- Limited available power on the moon, perhaps in 50-100 kW range
- Possible Solutions
  - High efficiency components are needed to minimize mechanical/electrical losses
  - Hybrid or advanced cutting system to make rock fragmentation more efficient
  - Mini Nuke 4x4x4 m yielding 1 MW



Challenges for the Lunar TBM - Wear

- Wear and Abrasivity of the Material
  - Volcanic rocks and regolith are known to be very abrasive
  - High wear of steel disc cutters to be expected
- Possible Solutions
  - New material for ring may be needed to reduce the weight and wear on the rings
  - Hard facing and coatings could be considered
  - Recycle parts and reuse them to save full replacements

Challenges for the Lunar TBM - Vacuum

- Lack of atmosphere and vacuum
  - No flushing medium for cooling/heating
  - Pressurization of the work areas
- Possible Solutions
  - Seal and pressurize the tunnel as you go
  - Airlocks for material transport and muck removal from cutting chamber and for portals/shafts
  - Seal the face, since repair and maintenance in space suit not suitable

Credit: Team Gamma, NASA 3D Printed Habitat Challenge Team

Challenges for the Lunar TBM - Fluids

- Lack of flushing medium
  - Energy of excavation turns to heat needs to be dissipated
  - Motors need cooling
  - Weight of the fluids as lubricant
  - Checking and testing of the fluids
- Possible Solutions
  - Pneumatic flushing
  - Closed loop heat exchanger

Challenges for the Lunar TBM - Thermal

- Extreme Temperatures
  - Cooling/heating
  - Complexities in operating the airlocks
  - Material disposal and muck transport issues
  - Surface operation and support in cryogenic conditions, could reach the face

- Possible solutions
  - Thermal extreme could mitigated with depth
  - Operation under extreme temperature

Challenges for the Lunar TBM - Stability

- Ground Stability
  - Unknown ground conditions
  - Mixed ground is the most difficult cutting conditions for TBM, having soft ground and hard rock at the face
  - Dissimilarity of materials in high stress conditions will lead to instability
- Possible Solutions
  - Ground support with wire mesh or segments may need to be updated to other spray on linings

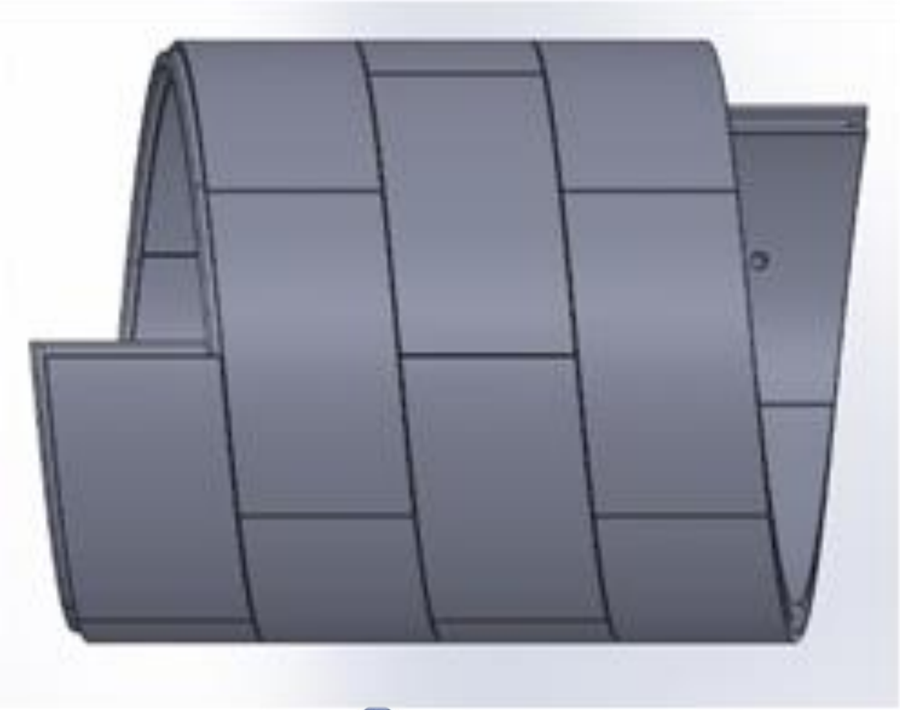
Challenges for the Lunar TBM – Sealing

- Maintaining Air Pressure in the tunnel
  - Sealed lining and tight shield/lining interface is necessary
  - Ground should be able to contain a 1 Atm internal pressure
- Possible Solutions
  - Contain the internal pressure ▪ Thin membrane ▪ Regolith additive manufacturing

- Insert pressure vessels – hard wall or inflatable

Helical Segments

- Allowing for continuous and air tight lining of the tunnel while TBM is operated
- Can be post tensioned to allow for more flexibility in loading



Challenges for the Lunar TBM - Utilities

- Utilities
  - Need for water, electricity, compressed air, ventilation for breathable air,
  - Communication and data exchange
  - Sensory/monitoring systems and instrumentation
- Possible Solutions
  - Bringing in from the surface
  - Habitat design

Conclusion

- Need for underground space for human habitats is imminent, and to develop and connect the spaces we need tunneling
- TBMs are the most efficient means of tunneling
- Operating TBM with current standards is not suitable for lunar applications
- Need to evaluate the individual components and assess the requirements for efficient operation of TBM
- Establish research needs to address the identified issues

Thanks

Questions?

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT