Space Resources Roundtable

LEAG
LUNAR EXPLORATION ANALYSIS GROUP

# Lunar Ice Mining Strategic Knowledge Gaps

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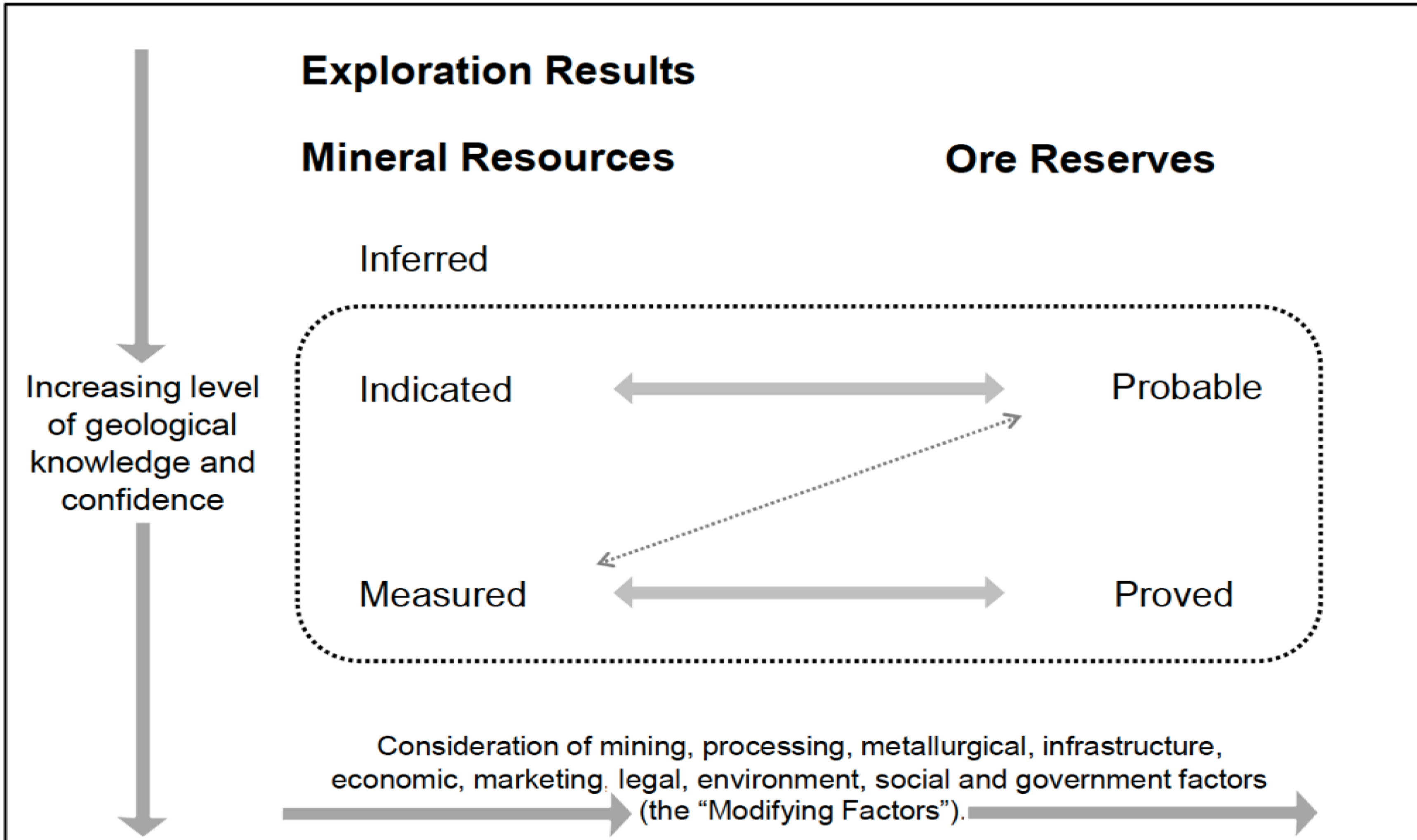
# Mining Strategic Knowledge Gaps

- Mining strategic knowledge gaps (SKG's) represent the totality of geologic and geographic information necessary to characterize lunar ice as a **proven reserve** of sufficient value to close the business case
  - Location and richness of ice deposits
  - Physical characterization of icy regolith
  - Geographical/operational considerations
    - Proximity to sunlit areas
    - Sites for propellant processing & landing/launch pads
    - Suitability of surface for transport vehicles

# Developing a Proven Reserve




JORC, 2012. Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code) [online]. http://www.jorc.org

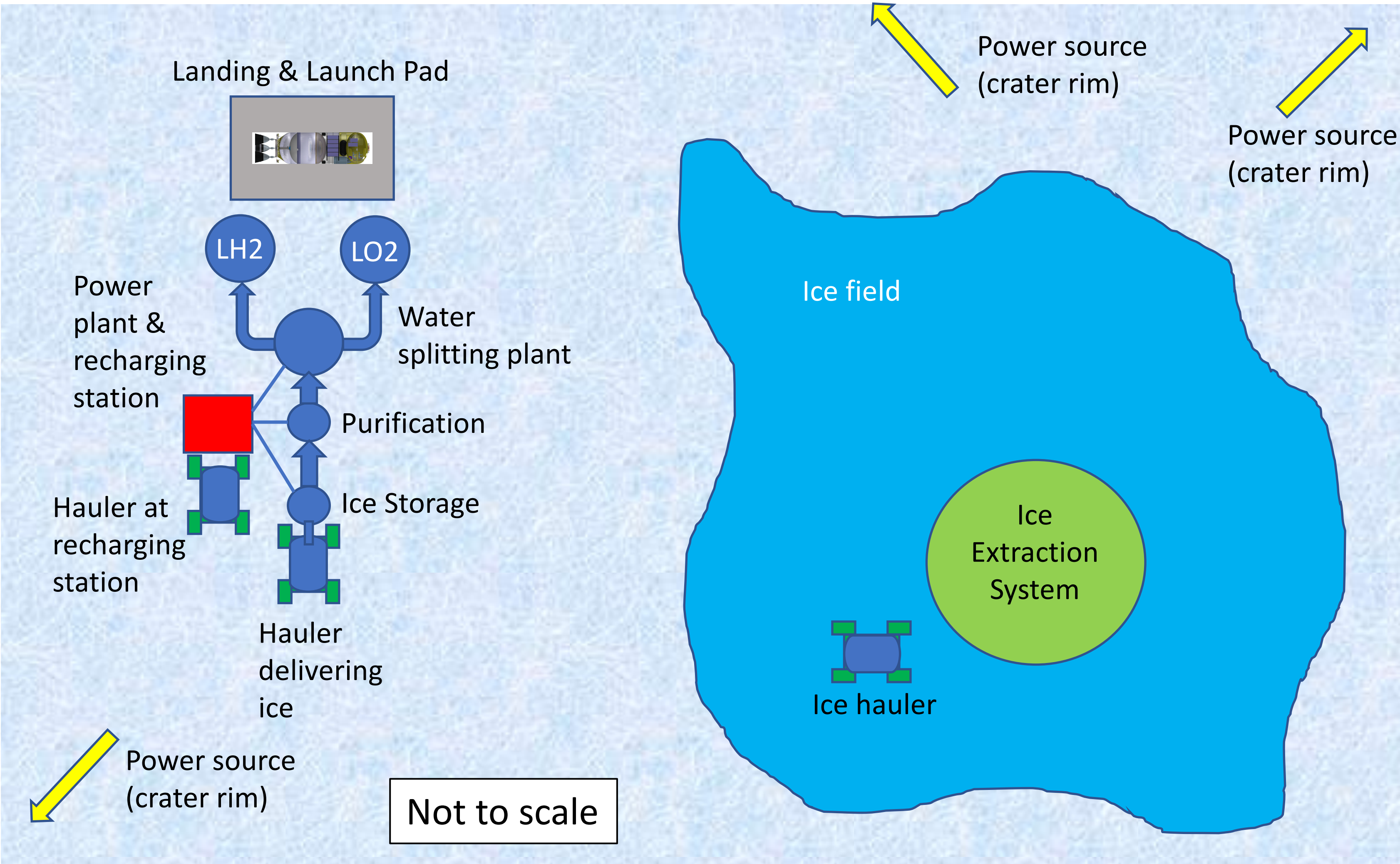
# Groundrules & Assumptions

- Reference business case was developed by ULA and CSM, presented at the SRR
- Lunar mining architecture study performed by CSM in 2017 & continued refinement via ULA sponsored workshops
  - Three mining approaches considered
    - Excavation & bulk heating of icy regolith
    - Subsurface in-situ heating and vapor collection
    - Surface in-situ heating and vapor collection
  - If effective, the in-situ heating methods will be lower cost and more robust

# The Anatomy of a Lunar Ice Mine

- Located within a permanently shadowed region (PSR)
- Autonomous or tele-operated operations
- Power comes from nearby permanently sunlit regions (option for nuclear power located within the PSR)
- Centralized LO2/LH2 propellant processing & storage facility located near a landing/launch pad
- Ice extraction system located at ice field with transport to the processing facility

# Lunar Mining Architecture



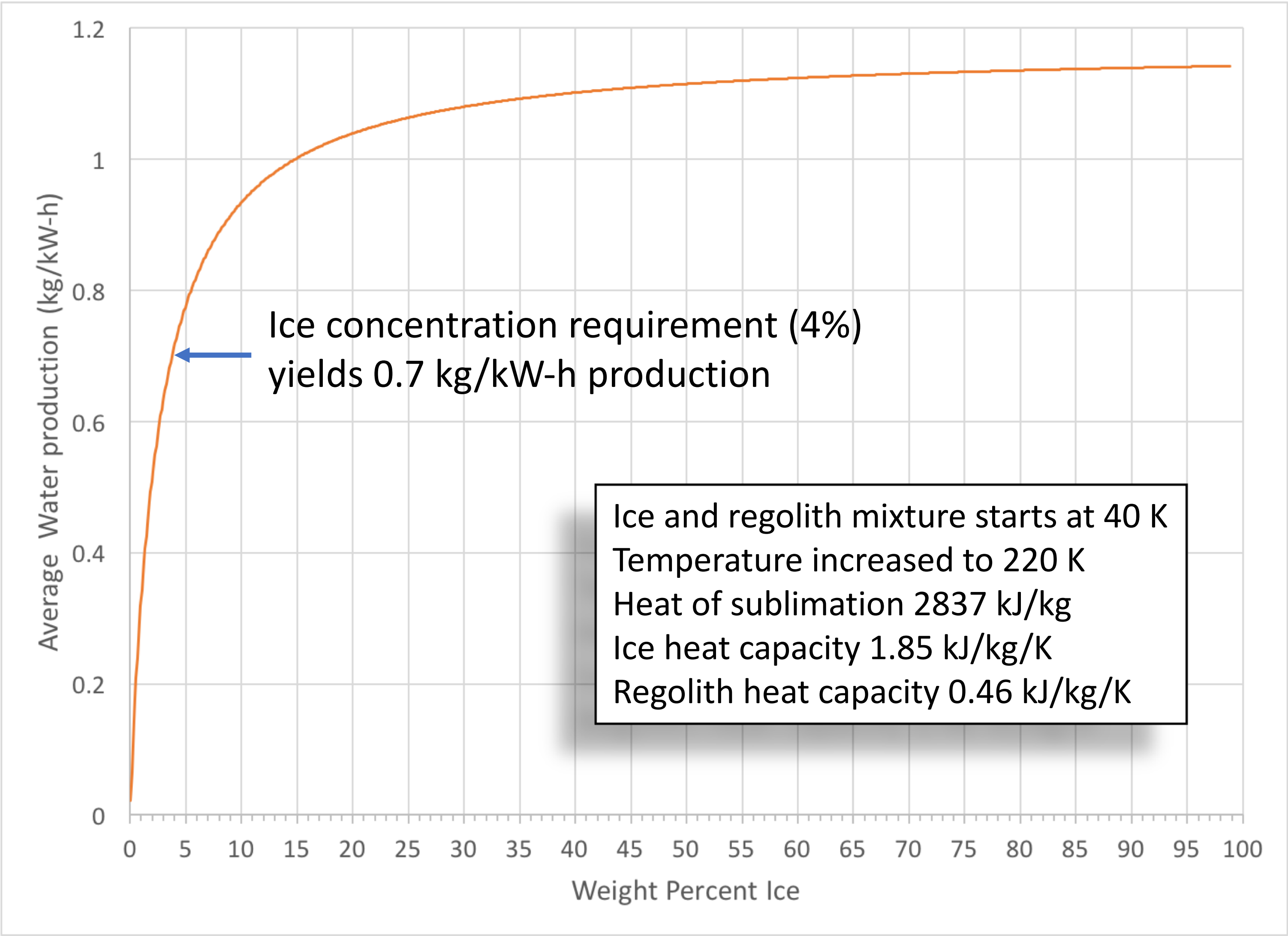
# Viable Ice Deposits

- Propellant production rate is the driving requirement for the required richness of economically viable ice deposits
  - 1100 mT/yr — Original ULA business case, 2016
  - 1200 mT/yr — Sowers PPP business case, 2018
  - 1500 mT/yr — Current ULA workshop, 2018
- Mass of ice mined must be 1.54 times greater
  - Assumes propellant mixture ratio = 5.5 (LO2 to LH2)
  - **1700-2300 mT ice/yr**
- 10 year mine life assumed in the business case
- **Viable ice deposit must contain ≥ 25,000 mT of extractable ice**

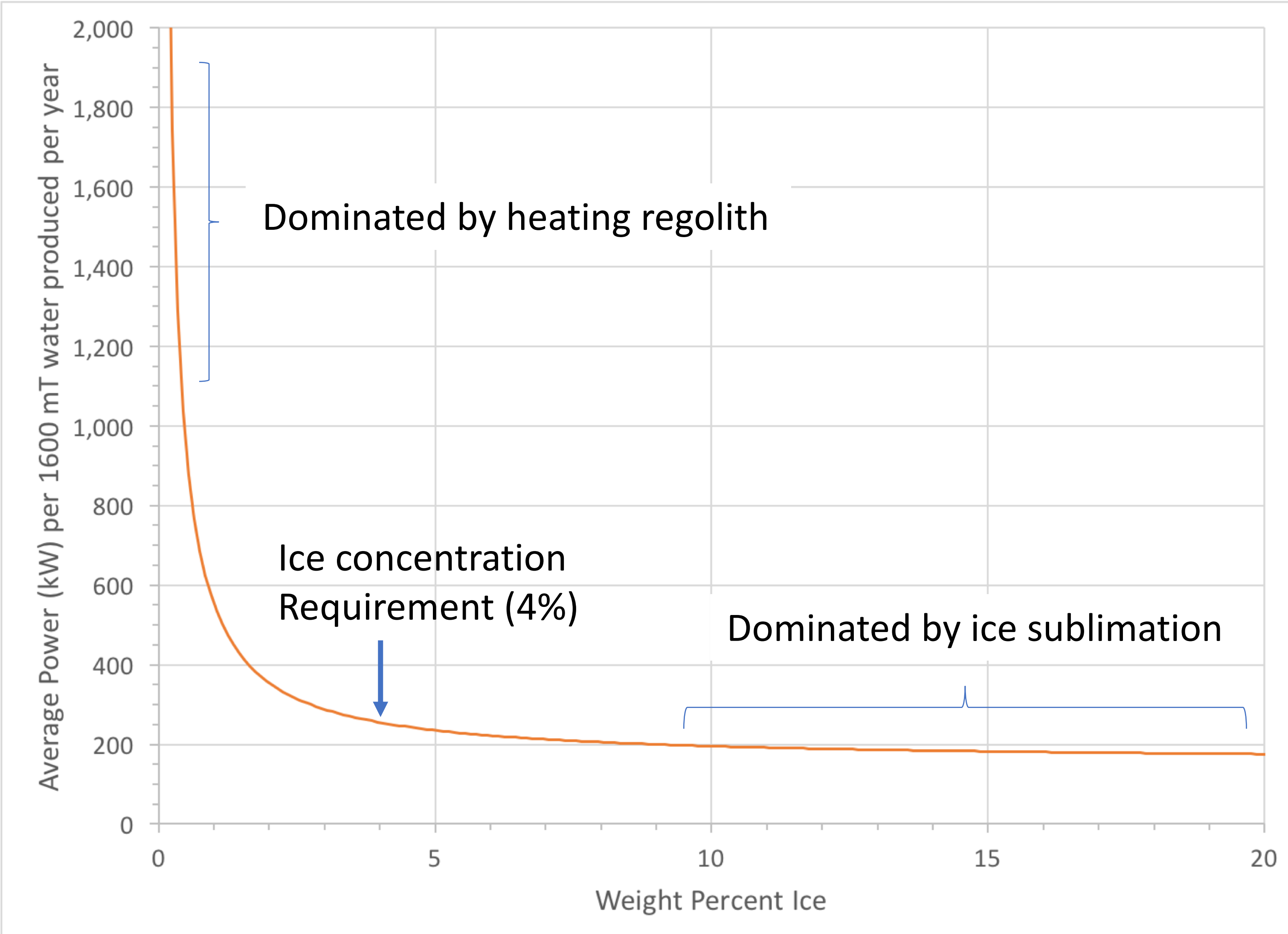
# Viable Ice Deposits, Cont'd

- Ice % by mass greatly affects the energy to heat and sublimate
  - **≥ 4% ice by mass** chosen as the knee in the curve to minimize power wasted heating regolith
- ~5% ice by mass inferred from LCROSS data
  - Cabeus crater

# Ice production versus ice mass fraction



# Power versus ice mass fraction



# Viable Ice Deposits, Cont'd

- Average ice density (kg ice/$m^3$ material) determines extent of the mining operation
  - Volume of material to be excavated (excavation methods)
  - Surface area to be heated (in-situ heating methods)
- Business case assumptions (surface heating):
  - **≥ 54 kg ice/$m^3$ (first meter depth)**
  - ≥ 27 kg ice/$m^2$ sublimated
  - ≥ 25 kg ice/$m^2$ captured
  - 100,000 $m^2$ mined per year
  - **≥ 1 $km^2$ required for 10 year life**
- Comparisons
  - Hard water ice = 900 kg/$m^3$
  - Snow = 90 kg/$m^3$
  - Regolith = 1300-1800 kg/$m^3$ (data from lunar equatorial regions)
  - Icy regolith mixture at 4% ice by mass yields 54-75 kg ice/$m^3$
- Is it dirty snow or frozen concrete?

# Viable Ice Deposits, Cont'd

- Other key parameters for all methods
  - Presence and amounts of other volatiles that will contaminate extracted ice
  - Heat capacities & other thermal properties
  - Depth distribution
- Other key parameters for in-situ heating methods
  - Porosity
  - Thermal conductivity
  - Electrical conductivity
- Other key parameters for excavation methods
  - Mechanical properties: strengths, ductility, hardness, etc.

# Operational Considerations

- For the identified economically viable ice deposit sites
  - Proximity to sunlit areas for power or light transmission
  - Suitable locations for landing/launch pad and processing facility
  - Relatively free of boulders, slopes or other obstructions
  - Characterization of surface for transportation
  - Characterization of natural environments
    - Dust, thermal, micro-meteoroid, radiation, etc.

# Mining SKG Summary

1. The location of economically viable ice deposits in the lunar polar regions
   - ≥ 25,000 mT ice
   - ≥ 4% ice by mass
   - ≥ 54 $kg/m^3$ ice within first meter depth (surface heating)
   - ≥ 1 $km^2$ area (surface heating)
   - The last two requirements may be relaxed for subsurface heating or excavation
2. The physical characteristics of icy regolith within the lunar PSRs
   - Density: bulk, ice, regolith
   - Porosity, thermal and electrical properties
   - Mechanical properties
   - Variations with depth
   - Presence and characterization of other volatiles

# Mining SKG Summary, Cont'd

3. Characterization of ice deposit sites
    - Proximity to sunlit regions
    - Nearby sites for processing and landing/launch
    - Surface
    - Environments

# Relevant LEAG SKG's

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# Open Science-Exploration SKGs

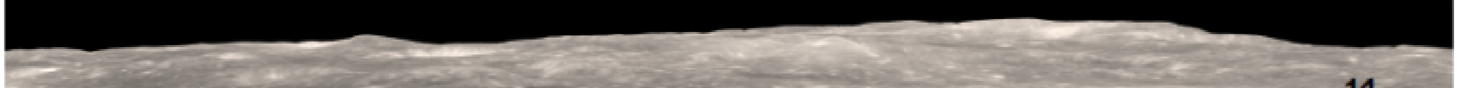
## **SKG Theme:** Theme 1 Understanding the Lunar Resource Potential.

**SKG Category:** I-D Polar Resources 3. Geotechnical Characteristics of Cold Traps.

**Narrative:** Landed missions to understand regolith densities with depth, cohesiveness, grain sizes, slopes, blockiness, association and effects of entrained volatiles.

**Enabling or Enhancing:** Enhancing for short-duration (≤ 28 days) lunar missions. May be enabling if trafficability is an issue. Enabling for long-term, sustained human operations on the Moon.

**Measurements or Missions Needed to Retire:** Can be addressed partially through remote sensing, additional observations, and data analysis. Requires ground truth at the 10 meter scale (laterally) over 1-5 km baselines. Must determine trafficability, compressibility, rolling resistance, bulk density variations, and grain sizes. These properties need to be verified through in-situ observations. Minimal information will be provided by rover tracks. A scoop with a variety of end effectors could be an interesting assessment tool. In-situ GPR measurements would also have value to characterize subsurface properties. LRO is providing relevant data at the 10-20m scale, particularly LOLA observations for South Pole during Extended Science Missions. Data at the meter scale requires landed rover mission. Some information on surface roughness could be obtained at the 1m scale with an imaging radar.



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## Open Science-Exploration SKGs

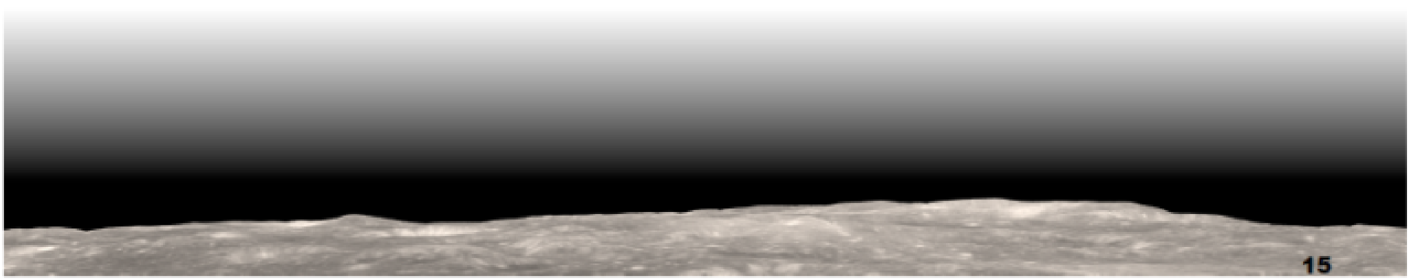
**SKG Theme:** Theme 1 Understanding the Lunar Resource Potential.

**SKG Category:** I-D Polar Resources 4: Physiography and accessibility of cold traps (robotic and human).

**Narrative:** Needs landed missions to understand slopes, elevations, block fields, cohesiveness of soils, trafficability.

**Enabling or Enhancing:** Enhancing for short-duration (≤ 28 days) lunar missions. May be enabling if trafficability is an issue. Enabling for long-term, sustained human operations on the Moon.

**Measurements or Missions Needed to Retire:** Landed surface exploration missions. Can be addressed partially through remote sensing, additional observations, and data analysis.



## Open Science-Exploration SKGs

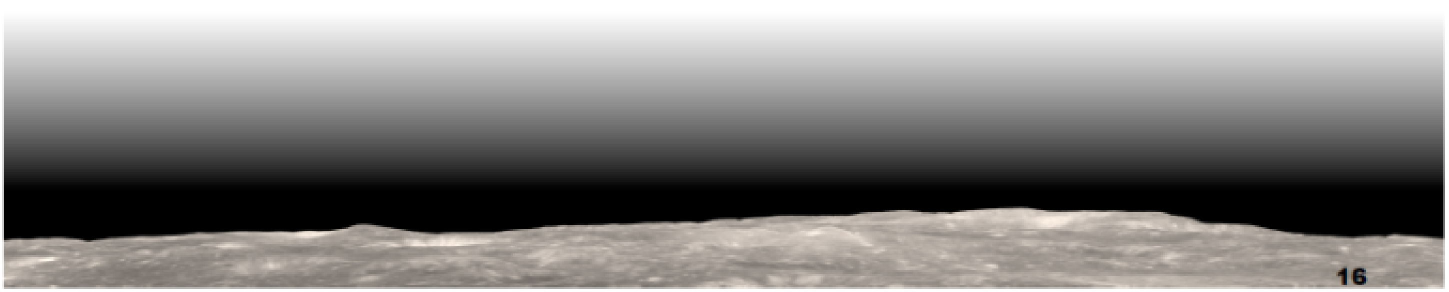
**SKG Theme:** Theme 1 Understanding the Lunar Resource Potential.

**SKG Category:** I-D Polar Resources 5: Charging and plasma environment within and near PSR.

**Narrative:** Landed missions to understand the charge reservoirs (plasma or ground) in the low conductivity environment. Limited plasma flow into PSRs may create poor electrical dissipation for tribocharging objects like drills, rovers, etc. The electrical 'ground' or reference point is not identified. Examine ion entry into PSRs as sputtering loss process.

**Enabling or Enhancing:** Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.

**Measurements or Missions Needed to Retire:** The electrical "ground" or reference point is not identified. Examine ion entry into PSRs as sputtering loss process. Moving a rover in and out of shadowed region provides ground-truth. Use wire in shadowed and sunlit region to check whether current gets induced. Implications for astronaut safety and long-term maintenance.



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# Open Science-Exploration SKGs

## **SKG Theme:** Theme 1 Understanding the Lunar Resource Potential.

**SKG Category:** I-D Polar Resources 6: Composition, Form, and Distribution of Polar Volatiles

**Narrative:** Water and possibly other exotic volatile species are present in lunar polar regions; must determine the form, concentration (including mineralogical, elemental, molecular, isotopic make-up of volatiles), and distribution of these species and how they vary from depths 0-3 m over distances of 10-100m scales. Required "ground truth" in-situ measurement within permanently shadowed lunar craters or other sites identified using LRO data. Technology development required for operating in extreme environments. Enables prospecting of lunar resources and ISRU. Relevant to Planetary Science Decadal survey.

**Enabling or Enhancing:** Enhancing for short-duration (≤ 28 days) lunar missions. Enabling for long-term, sustained human operations on the Moon.

**Measurements or Missions Needed to Retire:** Requires ground truth at the 10 meter scale (laterally) over 1-5 km baselines. Landed surface mission. Surface mobility is absolutely essential to be able to provide ground truth to orbital sensor datasets and characterize the regolith concentrations laterally at the 10s of meter scale over baselines of at 1-5 km. Two desirable instruments: (1) Gas Analyzer/ICPMS: Heat the soil, measure and determine the different species for H+ and OH contained within; similar conceptually to Viking GCMS experiments. (2) Neutron Spectrometer: bulk H/OH measurements to the 1-5 ppm level, including the subsurface to at least 2 meters depth. (3) UV/VIS/NIR spectrometer to assess presence of OH- (4) Multi-frequency GPR to assess subsurface distribution.

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