Lunar Polar Ice
Methods for Mining the New Resource for Exploration

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Mining Lunar Polar Ice

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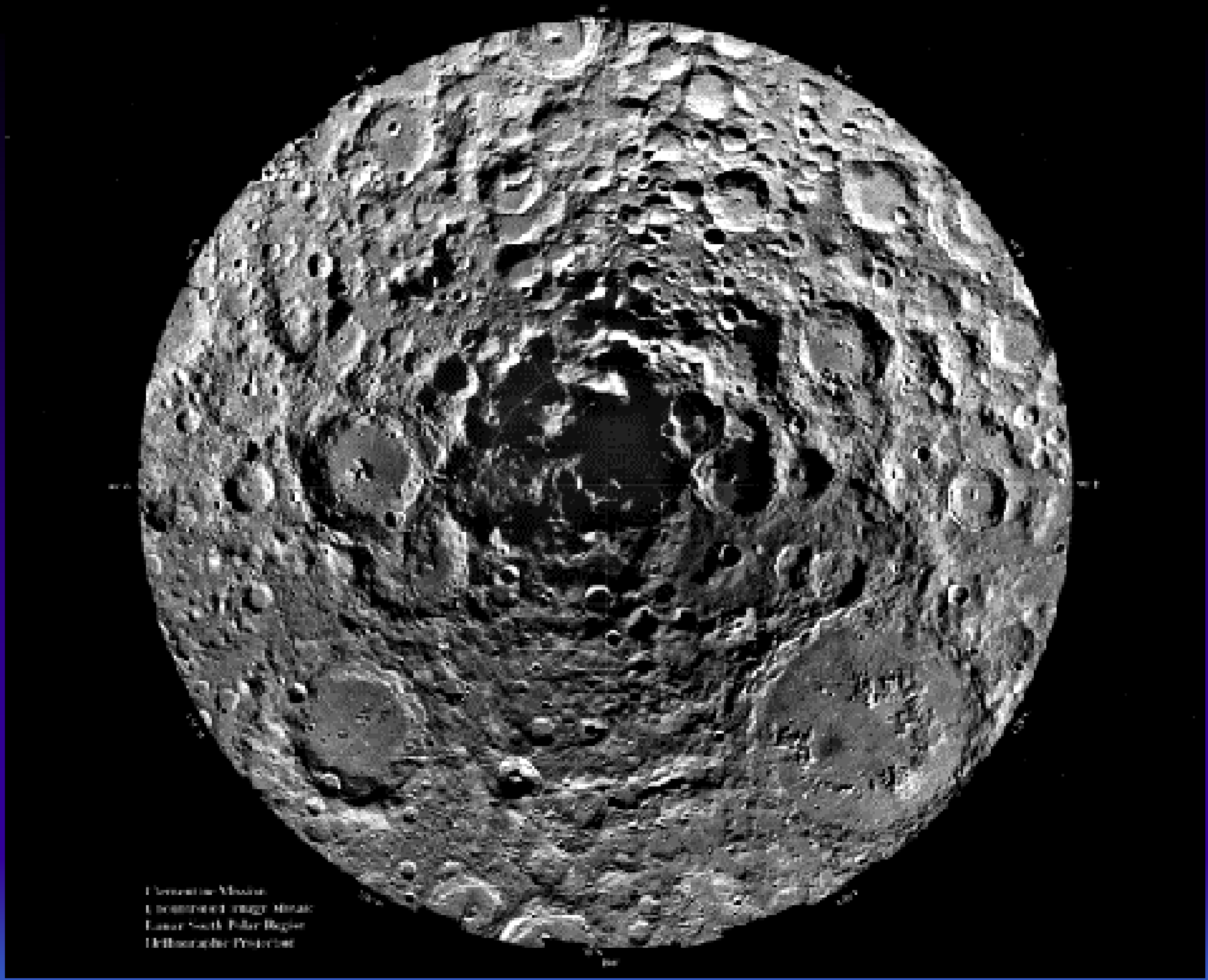
Purpose of the Study

- Assess approaches to extract and utilize ice if it exists in permanently-shadowed cold traps at the Lunar poles
- If high levels of hydrogen are observed by Lunar Prospector, additional missions including a robotic lander will be proposed
- An understanding of possible extraction techniques will aid in the design of experiments and technology demonstrations for these surface missions

Evidence of Lunar Ice

- Interest in ice on the Moon was stimulated by the Clementine mission
- Clementine mission demonstrated extensive areas of permanently shadowed terrain at the lunar poles (especially the South Pole)
- A bi-static radar signal received in one pass over the South Pole was interpreted to indicate the presence of ice, although that observation was later challenged

Lunar South Pole

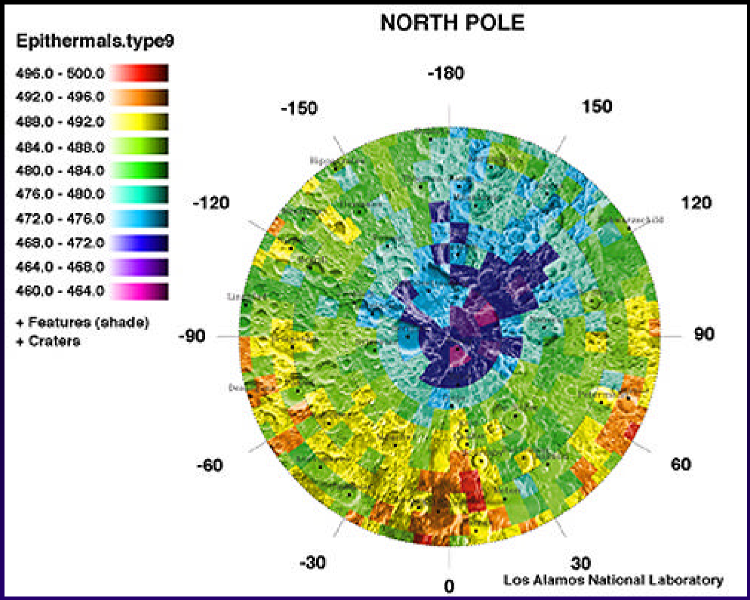


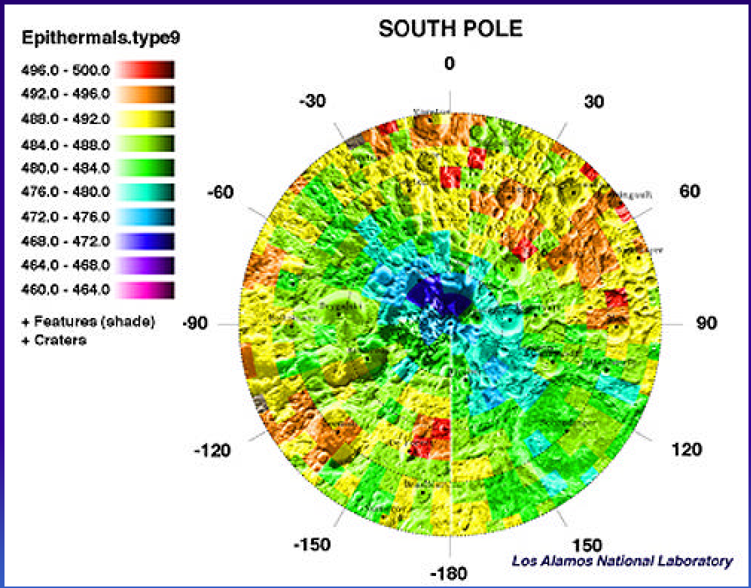
Evidence of Lunar Ice

- On January 6, 1998, Lunar Prospector was launched carrying an experiment called the Neutron Spectrometer
- This experiment was designed to detect hydrogen, which would indicate the presence of water ice on the Moon
- Analysis of the initial data indicated water ice mixed in the lunar regolith at relatively low concentrations (0.3 - 1 percent by mass) up to a total of 300 million metric tons

Data from Lunar Prospector

- Subsequent data indicates that the lunar poles may contain up to 6 billion metric tons of water ice
- The neutron data maps for the North and South Pole of the Moon show the dip in the neutron signal (blue and purple regions)
- This dip in the neutron signal is consistent with the signature of water ice





Data from Lunar Prospector

- New analyses indicate discrete, confined, near-pure water ice deposits buried beneath up to 40 cm of dry regolith
- The ice deposits are confined to an area of ~1,850 km^2 at each lunar pole to a depth of 2 meters (regolith mixing over past 2 billion years)
- Lack of a fast-neutron hydrogen signature rules against surface deposits, so it is unlikely the hydrogen is due to solar wind
- The water signature is 15 percent stronger at the North Pole than the South Pole

Importance of Lunar Ice

- Source of rocket fuel and oxidizer for a low-cost Moon-to-space transportation system
- Life support for future manned Lunar exploration
- Study of relatively pristine cometary or asteroid material
- Scientific interest in verifying numerical models of ice accumulation/deflation in permanently-shadowed polar cold traps

Sources of Water

- Micrometeoroids
  - Contain up to 10% water
  - Some water may migrate across the surface to the polar cold trap after impact
- Solar wind hydrogen reduction of the Lunar regolith
- Comets
  - Contain up to 50% water and other volatiles
  - Significant amounts of water from short-period comets may be retained (low strike velocities)

Amount of Water

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- 20%-50% of water molecules released on the Moon would be deposited in the cold trap
- Estimated amount of water deposited in the cold trap in the last 2 billion years
  - Micrometeoroids 10^{17}g
  - Solar wind hydrogen reduction 10^{17}-10^{18}g
  - Comets 10^{17}-10^{18}g
- Six billion metric tons of lunar ice estimated from the Lunar Prospector data is about one order of magnitude less than theoretical model

Loss Mechanisms

- Sublimation
- Sputtering
  - Due to the Solar wind
- Radiation
  - Removal by H Lyman Alpha radiation from the local interstellar medium
- Micrometeoroid vaporization
  - Erosion rate on rock surfaces is known to be ~1mm/my

Preservation of Ice

- Loss mechanisms greater than the steady-state migration of water to the cold trap
  - Cometary layer thicker than 1 mm will survive and be covered by regolith in 1 million years
- Loss mechanisms equal migration rate
  - Original cometary layer will be preserved
- Deposition rate faster than loss mechanisms
  - Cometary ice will grow with ice and dust deposits on the surface

Ice Recovery Approaches

(1) In-situ heating of the ice/regolith

- No excavation of the ice/regolith mixture
- Water vapor is frozen at the surface for transport

(2) Excavate the ice/regolith and process it in a furnace located in the cold trap

(3) Excavate the ice/regolith and transport it to a sunlit area for processing

Elements of the Extraction Approaches

- Ice/regolith preparation or collection
- Energy source
- Energy delivery to the excavation and extraction sites
- Water ice extraction process
- Ice or ice/regolith transportation out of the permanently-shadowed area

Element Matrix

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Ice/Regolith Preparation or Collection	Energy Source	Energy Delivery to Shadowed Area	Water Ice Extraction Process	Ice/Regolith or Water Transport
Ice/Regolith Preparation - Hammer & scoop - Air hammer - Auger - Block cutting - Explosive	Electrical - Nuclear reactor - GPHS-RTG - Chemical reactor - Fuel cell - Photovoltaics	Electrical energy - Wires, cables - Fuel cells - Batteries - Beamed power	Vaporization - Microwaves - Electrical furnace - Beamed heating - Chemical	Pipe out of shadow - Liquid water - Steam/vapor Tanks on rovers
Ice/Regolith Collection - Scoop - Auger - Drag line bucket - Bulldozer	Direct Heating - Nuclear reactor - GPHS-RTG - Solar - Chemical - Laser	Thermal energy - Solar reflector - Insulated pipes - In-situ reactor - Beamed light - Chemical	Melting - Chemical - Solar - Nuclear - GPHS-RTG	Mechanical - Drag lines - Buckets - Gondolas - Conveyor belt - Dumbwaiter
		Mechanical energy - Cables - Belts	Condensation on cold plate	Ballistic - Rocket - Catapult

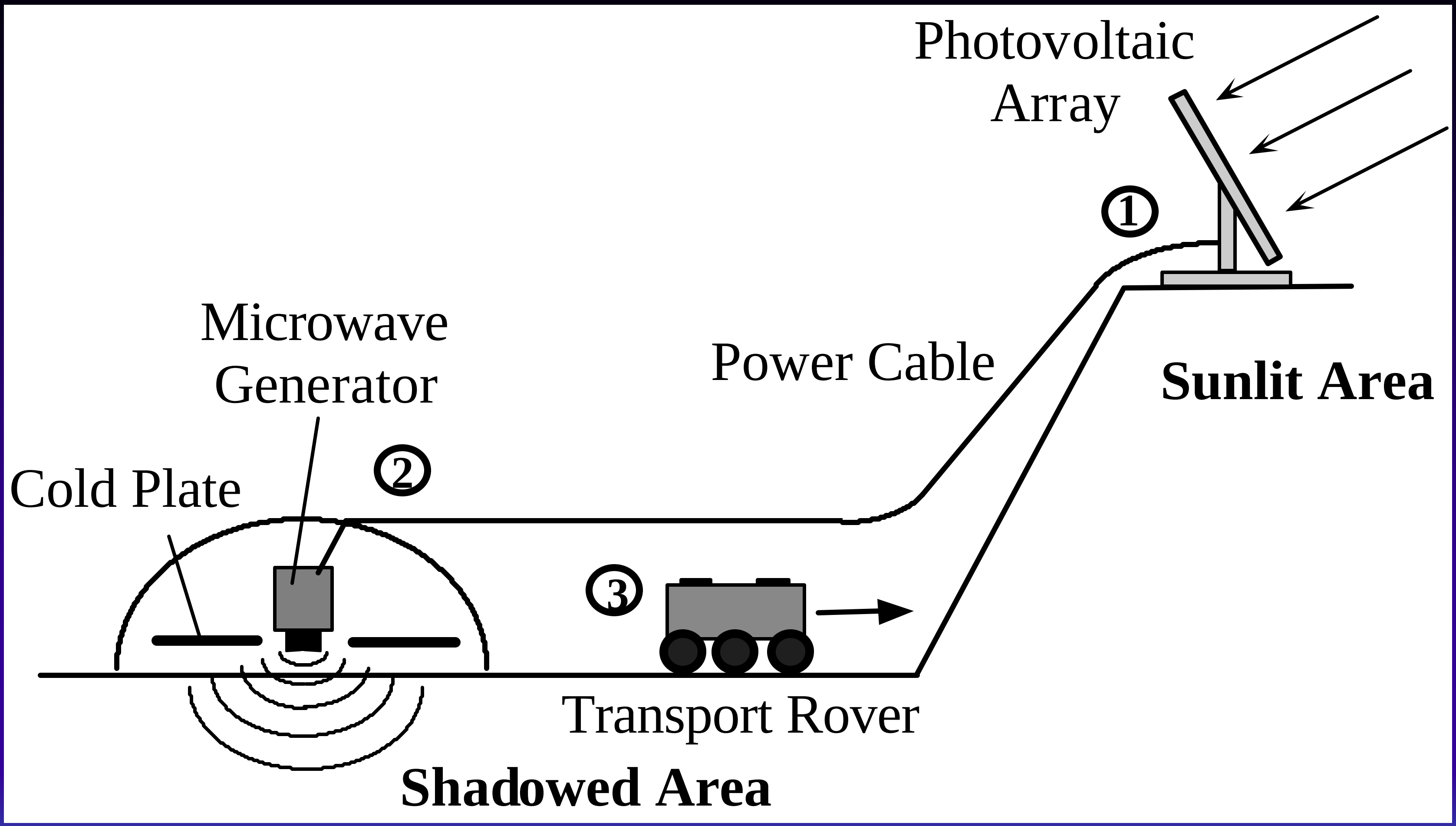
Evaluation Criteria

- Reliability, Life Expectancy, and Safety (8.3)
- Ability to Achieve Goals (8.1)
- Performance (8.1)
- Cost (7.4)
- Technical Risk (6.6)
- Crew Time Requirements (6.3)
- Versatility/Flexibility (5.8)
- Lunar Environmental Impact (3.8)

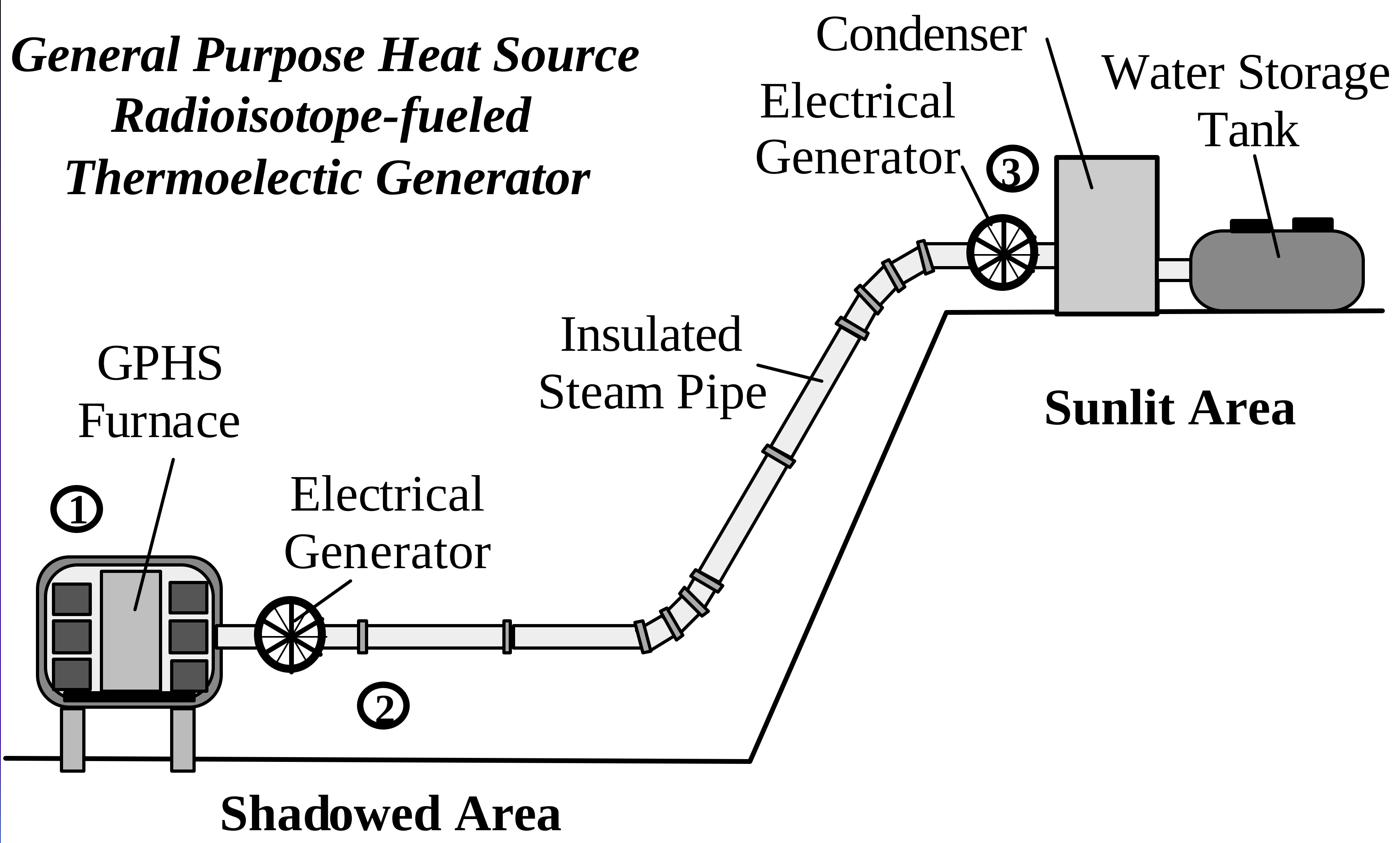
Extraction System Descriptions

- A system description was developed for each of the three basic extraction approaches
  - In-situ Extraction via Microwave Heating
  - Local Water Extraction with GPHS-RTG Thermal Processing and Pipe Transport
  - Drag Line Removal of Ice/Regolith with Solar Thermal Processing Outside the Permanent Shadow
- Represent only three combinations of the many possible elements that could be used

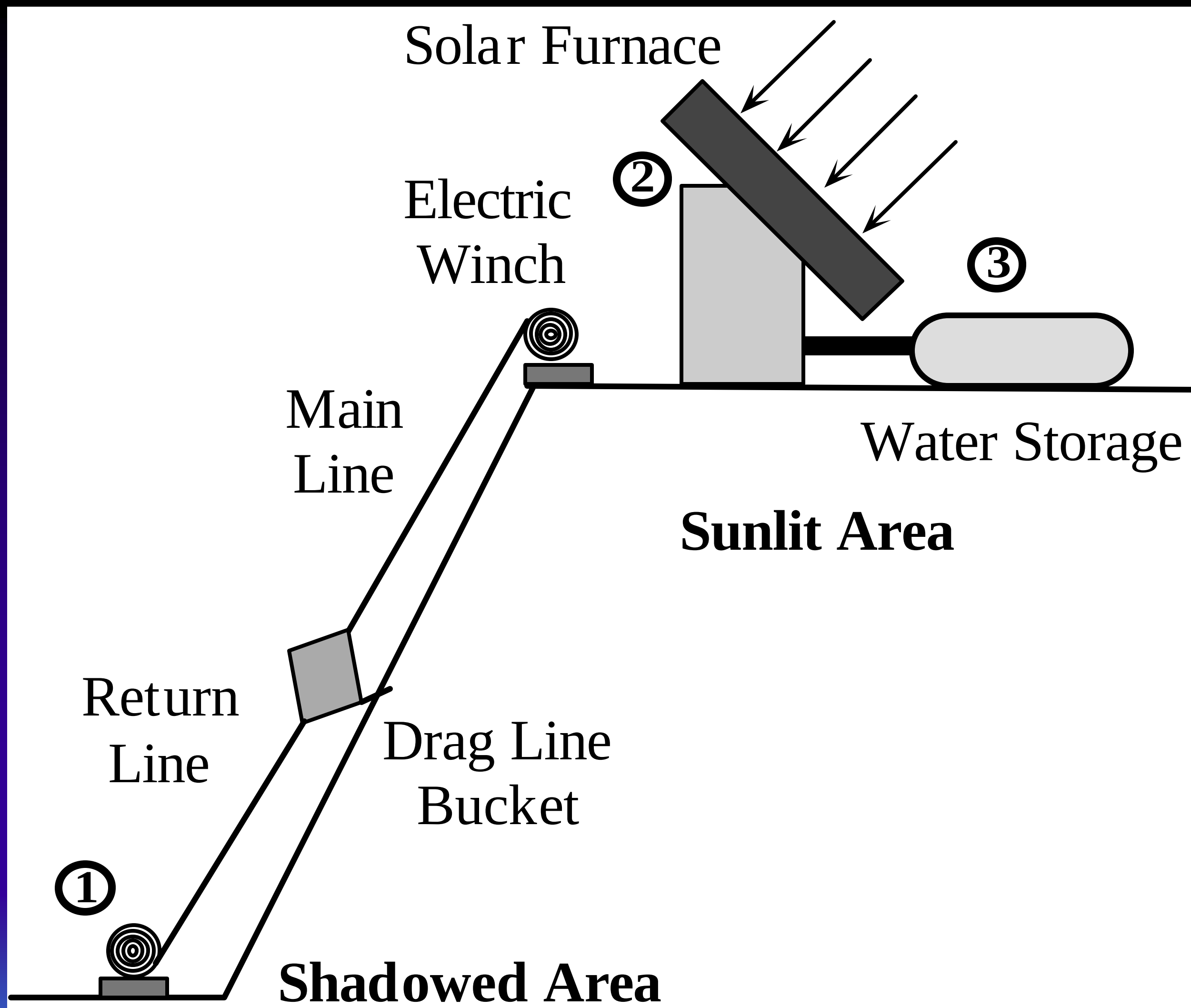
In-situ Extraction via Microwave Heating



Local Ice Extraction with GPHS-RTG



Drag Line with Solar Thermal Processing



Preliminary Evaluation

- A preliminary evaluation of these three extraction systems has been developed
- Each scenario has advantages and disadvantages depending on the elements selected and the properties of the lunar ice deposits
- More advanced assessments will be possible with more complete engineering models and when the higher resolution data from Lunar Prospector have are available

The Next Step

- The properties of the lunar water ice deposits need to be more accurately determined before a detailed mining and water extraction system can be designed
- A robotic lander/rover could directly measure some of the important characteristics of the ice deposits
- A lunar ice simulator will allow scientists to study the ice deposition process and measure the physical properties of the ice and regolith mixtures
- A large scale simulator will allow sub- and full-scale testing of ice extraction systems

Conclusion

- Purpose of this study was to assess the approaches to extract and use Lunar ice
  - Models of the physical properties of the Lunar ice and the environment within it exists
  - Various extraction concepts developed
  - Evaluation criteria determined for future use
- The data from Lunar Prospector indicate a significant amount of water ice on the Moon
- It is very important to understand how to best use this resource for scientific investigation and future space exploration