Space Resources

Michael B. Duke
Colorado School of Mines

Topics

- What are the resources of space?
- Rationale for developing space resources
- Elements of a space resource development program
- Economics of space resource development
- Scale of early development is consistent with current capabilities of robotic spacecraft
- Levels of complexity
- Goals for next decade
- Exploration goals for Moon, Mars, Phobos/Deimos, asteroids
- Technologies
- Policy

What are the Resources of Relatively Near-Earth Space?

- Energy
  - Abundant sunlight (less with increasing distance from Earth)
  - ^{3}He (Moon, atmospheres of outer planets)
- Materials
  - Water, oxygen (Lunar poles, Moon, Mars, carbonaceous asteroids)
  - Inert gases (Mars, low concentrations on Moon)
  - Metals, non-metals (Moon, Mars, stony asteroids)
- "Real Estate"
  - Microgravity, access to vacuum, view of Earth
  - Planetary surfaces

Why Should We Develop Space Resources?

- Humans won't spread far beyond Earth unless we develop the capability to utilize space resources for basic needs
- The cost of robotic and human activities in space or on the surface of the Moon or Mars can be reduced by offsetting the need to bring propellants from Earth at high transportation costs
- New commercial opportunities can be opened in space by providing alternative, lower cost sources of needed materials
- A prosperous Earth in the long term may require the development of the energy resources of space (while providing an enormous commercial opportunity)

Longer Term Applications

- Other possible uses for space resources potentially offer significant returns
  - New Earth orbital operations architectures
  - Construction of solar power satellites or lunar power systems that beam energy to Earth
  - Low-valued major constituents of asteroids (water, metals) for use in space
  - High-valued minor constituents of asteroids (e.g. Pt, Pd, Ir) for use on Earth
  - ^3He from the Moon for fusion energy
  - Wide range of materials for space industrialization (products manufactured in space for use on Earth)

Rationale for NASA Investment in Space Resources

- Reduce the cost and therefore increase the likelihood of undertaking NASA exploration missions (particularly human missions)
- Encourage the development of commercial activities in space that can impact future U. S. economy
- Increase chances for technology synergies (e.g. life support and propellant production systems may require similar separation technologies)
- Programmatic: Foster integrated program thrusts (Planetary Exploration, Microgravity Sciences, HEDS, Technology)

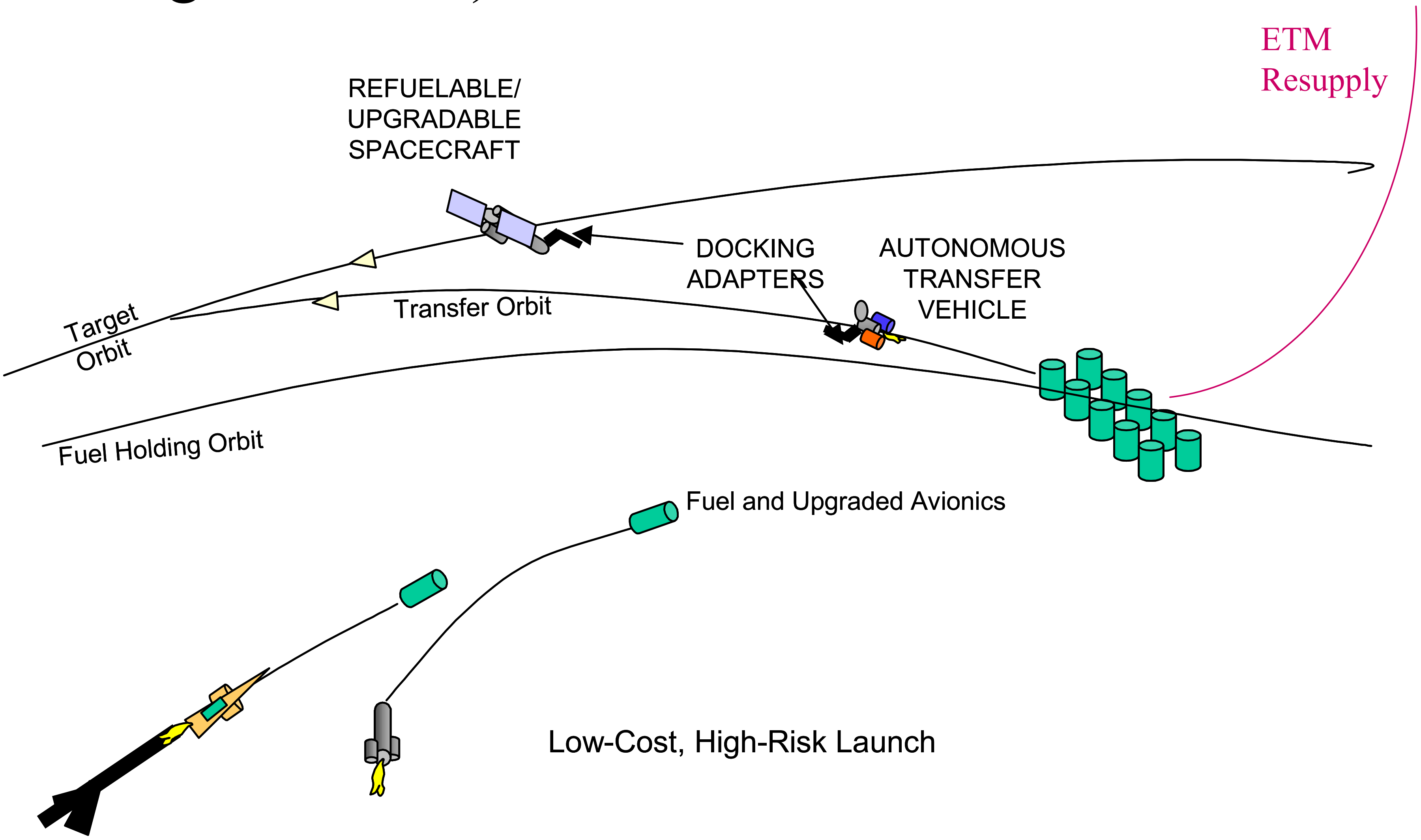
NASA Mission Applications

- Propellant production for return trips to Earth (can cut mass launched to LEO for Moon and Mars round trip missions by 1/2 –3/4) – significant reduction in cost of human missions
  - Mars – CH_4/O_2
  - Moon – H_2/O_2 from polar ice or lunar regolith
  - Asteroids – H_2/O_2 from hydrated C-asteroids
- Life support consumables for humans (caches reduce risk for human missions)
- Energy for human outposts
  - Silicon solar cells made in-situ
- Construction associated with human outposts
  - Radiation shielding
  - Lunar and Mars outpost construction applications

Earth-Orbital Propellant Depots

- DARPA “Orbital Express” architecture conceived for military satellite servicing
  - Primarily refueling of spacecraft whose orbits may change frequently
- Orbital propellant depots also would allow fueling of vehicles destined for HEO, Moon, Mars
  - Commsats might become a commercial market with upper stage fuel provided in LEO (equatorial orbit?)
  - Reusable orbital transfer vehicles would save additional Earth launch mass, reducing operational costs
- Similar propellant depot at L-1 for Moon and beyond
- Could these be supplied with lower cost propellant from Moon or asteroids?

DARPA Orbital Express Architecture (with ETM Augmentation)



Silicon Photovoltaic Cells on the Moon

- Solar energy is abundant on the Moon
- Silicon photovoltaic devices made of lunar materials might be deposited directly onto the lunar surface, avoiding cost of transporting structural materials
- Most of the components of the PV devices are naturally available on the Moon (Si, Al, SiO_2)
- A conceptual system has been defined to emplace silicon PV cells – sequentially smooths, melts upper regolith surfaces, vacuum deposits PV cell components
- In principle, an Athena rover scale machine could emplace hundreds of kilowatts of power capability in a year
- Research is underway (fitfully) to learn how to produce PV-grade silicon on the Moon

Human Energy Use *(D. Criswell)*

- Average electrical power use in developed nations (300 million people) is ~ 2 kW/person; in the rest of the world, ~0.3kW/person (4.3 billion people).

- Current world electricity production is ~1.9 billion kW

- By 2050, there will be 10 billion people. If the standard of living of the whole world approached current western standards, 20 billion kW would be required. Two possibilities exist:

  - Living standards will remain low for much of the world

  - Additional sources of energy will be developed.

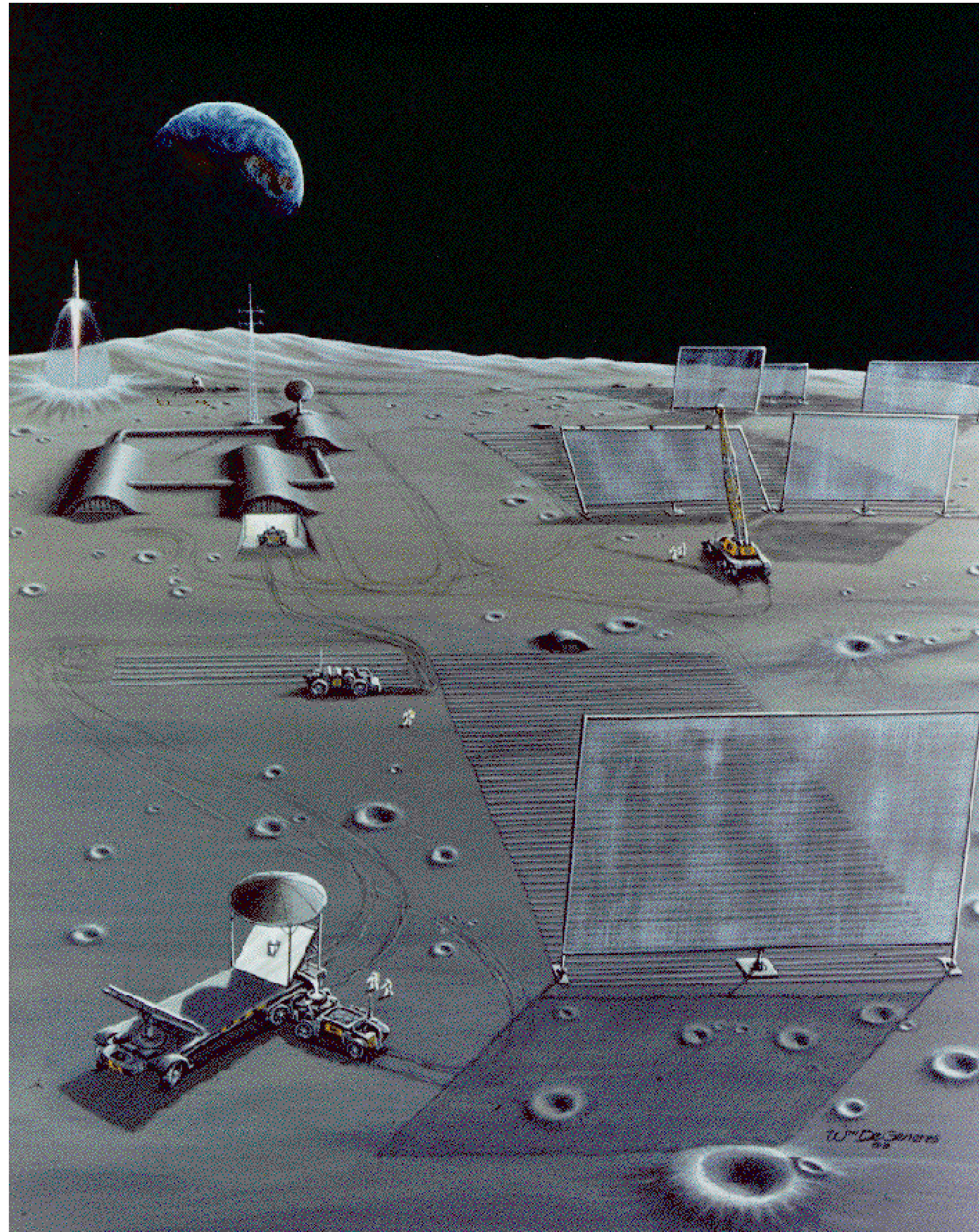
- Energy from space could be inexhaustible, clean, and inexpensive (Solar Power Satellites, Lunar Power System)

Lunar Power System (D. Criswell)

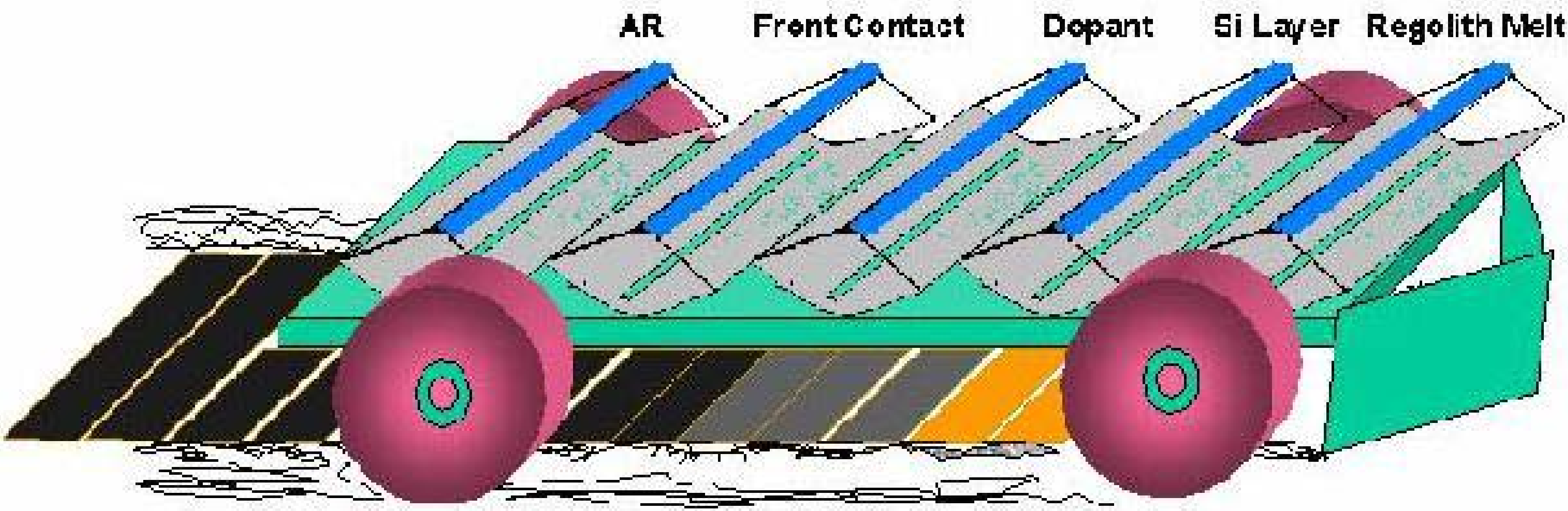
PV arrays deposited directly onto the lunar surface

Power collected in individual plots

Wire mesh antennas transmit microwaves to Earth (a giant phased array, electronically steered, far field optics)



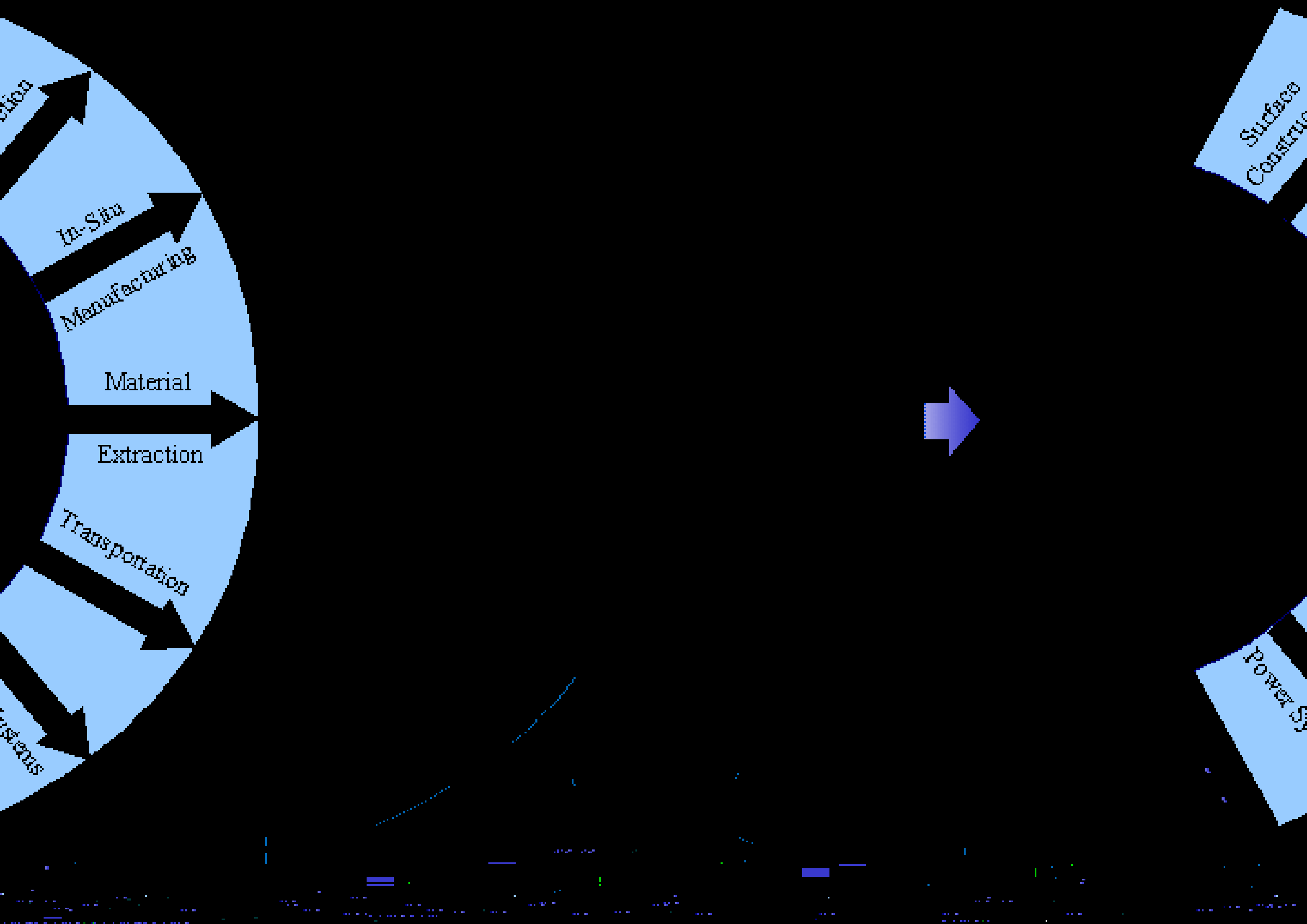
“Crawler” traverses Lunar surface, smoothing, melting a top layer of regolith, then depositing elements of silicon PV cells directly on surface



Concept due to A. Ignatiev, U. of Houston (NIAC)

Elements of a Space Resources Architecture

- Exploration and development of resources
- Production of raw materials
- Extraction, refining to simple materials
- Manufacturing of more complex items
- Transportation
- Servicing



In-Situ
Manufacturing
Material
Extraction
Transportation
Surface
Power S

Economic Considerations

- For economic resource development, a need, or market must exist. Therefore, resource development can not be its own end
  - Definition of the market establishes the amount of product and the price at which it must be delivered
- Near- to mid-term potential markets include
  - Propellant for space science missions (Mars sample return)
  - Propellant in LEO (Orbital Express)
  - Propellant and energy for human lunar or Mars activities
- Long-term markets could include
  - Energy to Earth (solar, ^{3}He)
  - Material support to lunar or Mars outposts
  - Support of space industrialization, space tourism

Other Considerations

- The farther (energetically) from Earth the product is used, the more competitive it will be - using propellant to return a spacecraft on Mars is economically easier than lunar oxygen to LEO)
- The more complex the space production and manufacturing process, the more likely that a product will be brought from Earth for use in space – simple uses (like propellant) will be developed first
- Lower Earth-orbit and in-space transportation costs diminish the competitiveness of space resource applications, assuming that space resource development and operations costs are fixed

Cost/benefit

- Principal factors in determining cost of space resource development
  - Extraction, processing and manufacturing system development
  - Transportation of processing equipment to space
  - Operations (including maintenance and repair)
  - Cost of money (long development or delivery times undesirable)
- Benefits
  - Transportation costs offset by availability of space resources
  - New markets on Earth enabled by space resources
  - Strategic benefits (e.g. control of energy supplies)
- In determining cost/benefit, the utility, rather than simply the mass of the resource, must be compared
  - Example: A device made from asteroidal iron in space may not be as good as one made on Earth and shipped to space
  - Manufacturing costs must be included (simplest products are best)

Space Resources vs. Earth Supply

- For economic viability, the cost of using space resources must be less than that of the same product (with the same performance) delivered from Earth

Cost Element	ISRU	Earth
Development of product	H	L-M
Transportation	L	H
Operations costs	M-H	L-M
Cost of money (development and installation time)	M-H	L

Early Small Scale Applications can be Evolutionary from Current Robotic Missions

- A small amount of machinery operating for a long period of time and with low energy inputs can produce a great amount of product, which otherwise would have to be transported from Earth – drives autonomy/reliability/automated repair technologies
- Examples:
  - A Mars ISPP system with a mass of ~200 kg operating over 26 months could produces 10,000 kg of propellant that would otherwise have to be transported
  - Lunar ice excavation models suggest that a 200 kg system could produce 4000 kg/yr of propellant
  - Lunar silicon PV cell production estimates suggest a device with a mass of 200 kg could emplace 100's of kilowatts of power in a year
- Production of useful quantities are consistent with capabilities of current small robotic spacecraft for the Moon and Mars

Tim Muff Rover Sim

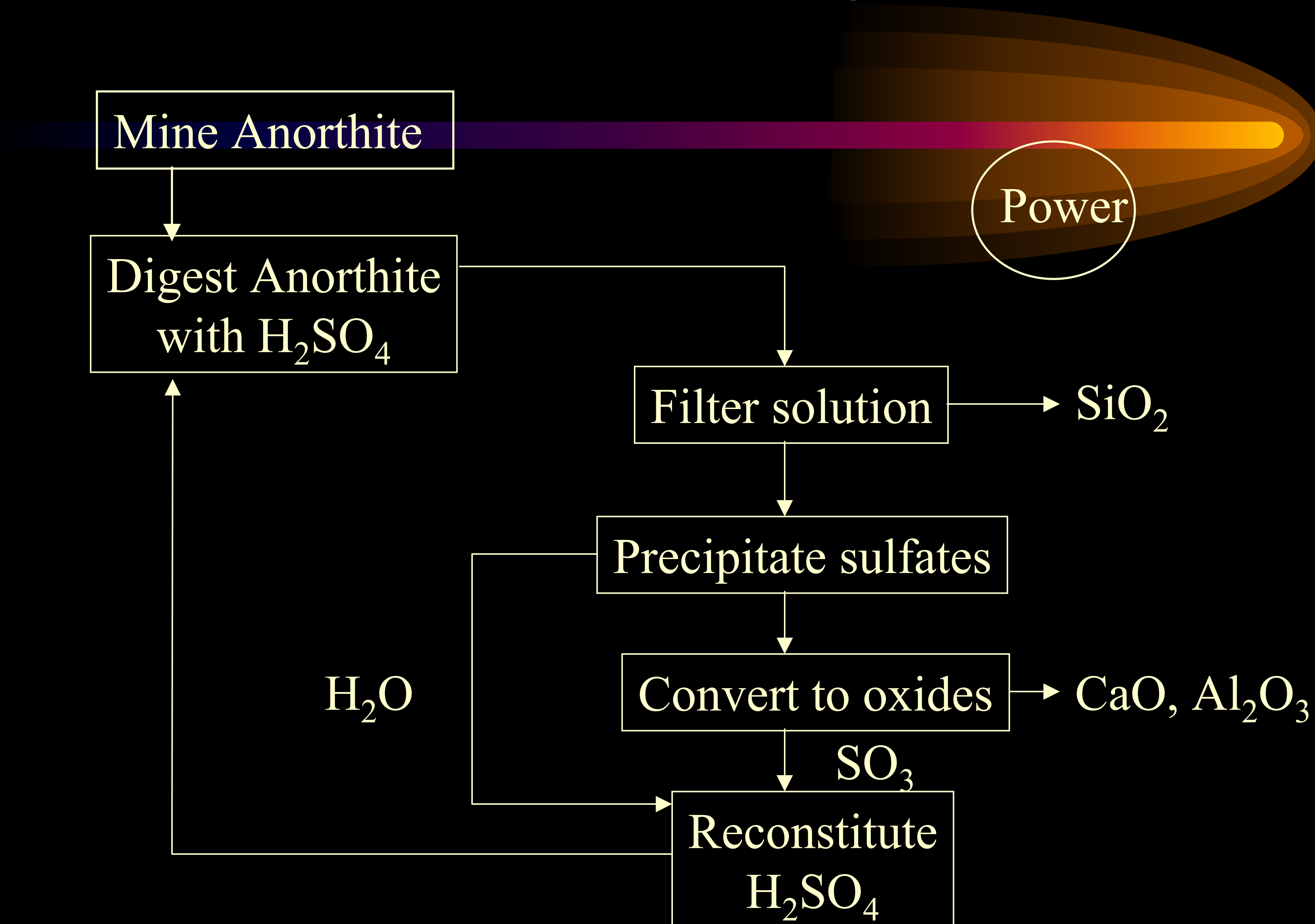
Complexity is an issue

- Various processes have different levels of complexity
  - Martian propellant for return trips to Earth
    - Pump atmospheric CO_2 split to retain O_2 and produce CH_4
  - Lunar polar water for lunar return trips and space propellant depot architectures
    - Excavate cold trap regolith, thermally extract water, electrolyze and liquefy to produce propellant
  - Photovoltaic cells produced from lunar materials
    - Produce Si from lunar materials, recover reagents, manufacture arrays
- At the lower end of complexity, precedents are available in the space program (e.g. life support systems for ISS)
- At the higher end of complexity, new technology and operations approaches will be needed

Example of Complexity: Processing Lunar Anorthite

- Lunar anorthite ($CaAl_2Si_2O_8$) is very abundant
- It could be a source for elemental silicon (PV cells), aluminum (electrical conductors), Al_2O_3 and CaO (cements, ceramics) and oxygen
- A process has been proposed by which anorthite is reduced to its oxide species:
- $CaAl_2Si_2O_8 \rightarrow CaO + Al_2O_3 + 2SiO_2$

Schematic of Anorthite Digestion Process



Challenges

- Excavation and material handling
- Staged chemical reactors for digestion, precipitation of dissolved solids, separation of liquids and solids, reactions between oxygen and solids
- Regeneration of reagents (full recovery desired)
- Reactor vessels (tanks), filters, stills, condensers, pumps, valves, storage reservoirs, etc.
- Energy and thermal engineering
- Implied surface transportation
- Energy systems providing thermal and electrical power
- System engineering and integration

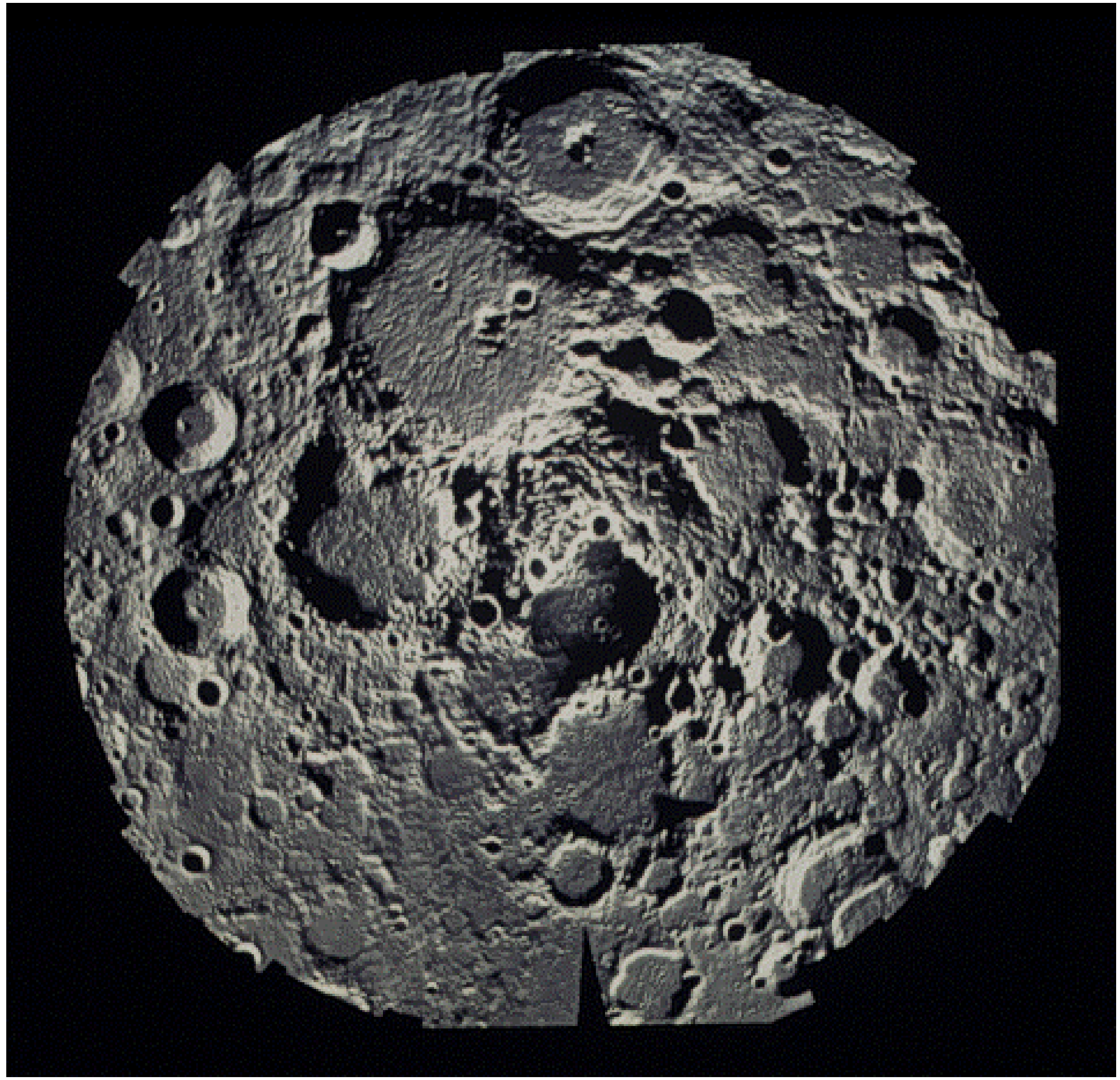
Goals for the Next Decade

- Exploration missions
  - Continue exploration to identify and characterize resources
    - Mars sample return; characterize distribution of water
    - Lunar polar exploration
    - Characterize and explore near-Earth asteroids
  - Conduct ISRU demonstration experiments on Moon and Mars in conjunction with scientific exploration missions
- Technology development
  - Demonstrate feasible techniques for producing energy and propellant based on space resources – focus on robotic systems
  - Long-lived, robust, systems requiring little or no maintenance
- Government Policy
  - Create an environment in which commercial development of space resources can begin
    - Provide guaranteed markets for resources from space
    - Provide incentives within exploration programs for space resource

Clementine Image of Lunar North Pole

Summer, noontime image. Shadowed areas are mostly in permanent shadow.

Lunar Prospector neutron spectro-meter has detected enrichments of hydrogen in the polar regions, consistent with cold-trapped ice



Lunar Polar Exploration

- Determine nature and distribution of hydrogen enrichments near lunar poles
  - History of cometary impacts (stratigraphy)
  - "Airless planet" surface phenomena
  - Form of hydrogen (vis a vis thermal extraction)
  - Distribution of hydrogen in upper few meters of lunar surface
- Demonstrate operations in permanent shadow
- Demonstrate extraction of hydrogen/water and production of propellants
- Can be carried out using robotic landers of same complexity no greater than Mars Athena rover

Martian Resource Exploration

- Atmosphere is well enough known for resource purposes
- Location of metal and non-metal concentrations will require detailed in-situ exploration at an appropriate time
- Water is the nearest-term, most valuable resource
    - Possibility of extraction from regolith clay minerals
    - Permafrost
    - Subterranean liquid water or brines
- Regolith and permafrost are possible near term sources
    - TEGA – like instruments for water characterization
    - Geophysical sounding to detect permafrost
    - Drilling technology eventually to tap liquid water, if it exists
- Resource exploration investigations and demonstrations should be included in robotic science missions (e.g. MIP)

Asteroid Resource Exploration

- Increasing discovery rate for near Earth asteroids
- Need to upgrade spectroscopic characterization capabilities to better identify asteroid chemical types
- Sample return missions to selected asteroids are required before economic recovery can be planned
  - Nature of asteroid regolith
  - Availability of resources
- Phobos & Deimos should be studied in a similar manner

New Technology is Needed

- A technology program is essential
  - Many techniques are complex, but not beyond the state of current technology for electrical and mechanical elements (equivalent to advanced life support systems)
  - Efforts to reduce the scale are important in translating terrestrial practice to the space environment
  - Durable mechanical systems with long times between failure in difficult environments will be essential

Technology Development

- HTCI has developed aggressive roadmaps for space resources technology development
  - **In-Situ Resource Assessment, Extraction, & Separation**
  - **Resource Processing & Refining**
  - **In-Situ Manufacturing**
  - **Surface Construction**
  - **Surface Cryogenic and Product Storage & Distribution**
- Space Resource Development should continue to be supported strongly within HTCI
  - **Systems and technology development aimed at long duration operations; and effectiveness in small scale systems**
- Supporting technologies, such as power, surface transportation, automation and robotics, etc. should also receive attention.

Policy

- Currently there is interest in Congress for NASA to find commercial (money-making) applications in space
- Space resource development could offer such an opportunity
  - In the 20-30 year time frame, could potentially yield enormous results
- NASA should seriously consider the best ways to promote space resources development

AIAA Recommendations to NASA (1997)

- Establish and implement a strategic plan for development/demonstration of ISRU technologies
- Establish a NASA office to focus research – this is not just a HEDS issue
- Provide opportunities for robotic flight demonstration experiments
- Consider ISRU applications in all human mission planning
- Encourage other government agencies, industry, and other organizations to jointly fund research
- Develop an annual conference dedicated to ISRU once NASA funding is in place

Backup Charts

Martian Resources

- Martian atmosphere
  - CO_2, Ar, N_2 (propellant, breathing air)
- Martian regolith
  - H_2O, metals, carbonates(?)
- Martian cryosphere and hydrosphere
  - H_2O
- Special deposits (e.g. evaporites, hydrothermal deposits)
  - Metals, scarcer volatiles (sulfates, chlorides, etc.)

Lunar Resources

- Mare regolith (Silicates and Ilmenite)
  - Metals and oxides, particularly Fe, Si, Ti, oxygen, glass, solar wind volatiles, including ^{3}He
- Highlands regolith (Silicates, predominantly anorthite)
  - Metals and oxides, particularly Si, Al, Ca
- Pyroclastic volcanic glass
  - Oxygen
- Lunar polar regolith
  - Water (?) or hydrogen, possibly other volatiles

Asteroid Resources

- Many different kinds of asteroids, presumable each of a single character
  - Metallic asteroids – Iron, nickel, noble metals
  - Stony and stony-iron asteroids – Iron, nickel, noble metals, silicon
  - Carbonaceous asteroids – Carbon compounds, water, volatile elements
- Phobos and Deimos are likely captured asteroids that may be carbonaceous

An Example - Propellant from Lunar Ice

- Assumptions: Significant quantities of ice exist on the Moon and are readily accessible
- Processing includes excavator, water extractor, electrolysis and liquefaction systems
- System mass-100 kg; System Power – 1kW (est. 30kg)
- Total production: 4000 kg H_2/O_2 per year

(note that this is equivalent to ~1kg/hr production rate, if the system operates less than half of the time)

- At a fixed base, with a long-lived system, the total mass of material can be 100's of times the mass of equipment
- However, if human maintenance is required, the payback will be smaller

Who is Working on Space Resources?

- A core of investigators in government, industry and academia
- NASA
- International – Japan, Germany
- Summary papers have been provided by:
  - E. E. Rice and R. J. Gustafson – AIAA 2000 –1057
  - G. B. Sanders – AIAA 2000 – 1062
- Space Resources Roundtable III– CSM October 24-26, 2001