ECONOMIC GEOLOGY OF LUNAR HELIUM-3

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The end of the Apollo Program found humankind, and the United States in particular, on the verge of the establishment; of bases on the moon, research stations in earth-orbit, and the statement of a realistic goal of a permanent foothold on Mars by the end of the Century. In the motto of the last Apollo mission to the moon, this could have been "The End of the Beginning."

This opportunity was not grasped. Consequently, it falls to the current generation to re-ignite John F. Kennedy's torch for space. The emotional and economic energy for that torch could be supplied by helium-3, rare on Earth, but discovered and sampled (see reports summarized by Taylor, 1982) by the Apollo astronauts and scientists. Helium-3 and several other potentially valuable by-products of its production are slowly but continuously implanted in the lunar soils by the solar wind. The workers at the Wisconsin Fusion Technology Institute, "Astrofuel" (Wisconsin, 1988). Some of the important results of the Wisconsin analysis are summarized here.

Inherently safe and potentially low cost fusion reactors fueled by helium-3 might become the basis for producing large quantities of continuously available electrical power in space, for highly efficient space propulsion to and from Mars, and for life giving by-products that insure the self-sufficiency of settlements on the moon (Kulcinski and Schmitt, 1987). Indeed, fusion power plants fueled by helium-3 from the moon could supply the electrical energy human civilization will require to maintain and expand its quality of life as we enter the Third Millennium (Wittenberg, et al, 1986) and as we move that civilization toward the stars.

A preliminary estimate (Kulcinski and Schmitt, 1987) of the commercial price of lunar helium-3 delivered to the Earth in the first quarter of the 21st Century is about $1 billion per metric tonne. This is roughly equivalent to $7 per barrel oil at today's prices. Its value today is about $2 billion per tonne if matched against the cost of fuels currently used to produce electricity. The foregoing estimates also do not take into account the value of by-products from lunar helium-3 production that will be needed in space or the value of the spin-off of Astrofuel related technologies.

The principle advantages of the helium-3 fusion power cycle over other nuclear cycles include:

1. About 99 percent of the energy released is in charged particles (protons) that are non-radioactive and that induce no radioactivity in other materials.
2. High efficiency (70-80 percent) in energy conversion due to the direct conversion of charged particles to electricity.

3. Less waste heat to be rejected due to high efficiency.

4. Energy of the few neutrons released (1 percent of total energy) is only one-fourth that released in other fusion cycles and create no significant quantities of long lived radioactive waste.

5. A potentially shorter time to licensed commercialization than for other fusion cycles due to absence of significant radioactivity and waste heat.

If our estimates of the price of delivered helium-3 for deuterium/helium-3 power plants prove correct, such power plants will provide much lower cost electricity as well as much less environmental impact than other potentially competing power sources in the 21st Century.

The only major technical disadvantage of the deuterium/helium-3 fusion cycle is that the ignition temperature required to initiate fusion is about four times higher that for the competing deuterium/tritium cycle. This disadvantage appears to be becoming less and less significant as new fusion confinement technologies are developed.

Sufficient helium-3 is available on Earth (largely from tritium decay and natural gas) for development and prototype testing of deuterium/helium-3 power plants. Therefore, the primary issues that must be addressed to determine the feasibility of a commercial helium-3 industry are, first, the technical and economic feasibility of deuterium/helium-3 commercial reactors and, second, the technical and economic feasibility of providing lunar helium-3 to fuel such reactors. This second issue can be resolved objectively through the art and science of economic geology. The outline that follows summarizes the parameters that would need to be considered in an analysis of the economic geology of lunar helium-3. (This Preface was derived from the Introduction of a paper by Schmitt, 1988.)

INTRODUCTION

Economic geology evaluations of Lunar He-3 should answer the question: Can lunar He-3 be sold on Earth with sufficient profit margins and low enough risk to attract capital investment in the enterprise?

Potential Value of the Resource/tonne

He-3: $1-2 Billion/tonne
Equivalent to a value of $6-12/tonne of regolith mined as compared to about $220/tonne for calcined kaolin ore
$3/tonne for rutile ore, and $220/tonne for perlite filter aid ore. The profit margin within each of these values is about 30-50%.

By-Products for use in space: $1 Billion/tonne He-3

Potential Resource Base
1,000,000 tonnes He-3

Probable Recoverable Reserves
25 tonnes He-3/km² of high Ti regolith mined to 3 m depth with 60% recovery of 30 ppm He average grade (after Cameron, 1988).

Demand
Unknown at this time, but potentially 100,s of tonnes by 2050.

Parameters to Consider in Economic Geology Evaluations
- Geology
- Exploration
- Access
- Mine Planning
- Mining
- Beneficiation
- Processing
- Support
- Finances
- Politics

GEOLOGY

General

Regional Targets
- Known old (mature) high Ti maria
  - High proportion of agglutinates and ilmenite
  - Low proportion of coarse grained material
- Inferred high-Ti Maria

Candidate Mine Site Considerations
- Regolith Depth
- Boulder Distribution
- Low Grade Unit Distribution
- Low Recovery Unit Distribution
- Available Dump Sites
General Regolith Geology Considerations

Composition
Fragment/size distribution
Heterogeneities
Regolith Breccia/Agglutinates
Cold Traps for He-3 that will enhance grade

New Data Required

First basic question is: Can sites for He-3 mining be selected from existing data with sufficient confidence to attract investors?

Answer is: We don't know yet, but is it worth investing significant resources to find out?

Second basic question is: Can D/He-3 fusion development proceed without the proof of He-3 reserves on the moon that can support commercialization?

Answer is: Probably not beyond the research phase.

Precursor Missions (if existing data proves to be insufficient to attract investors)

Target best candidate sites
Evaluate based on set criteria
Pick first site that meets criteria

ACCESS

Logistics Support Costs
Earth to moon
People/consumables/equipment
Moon to Earth
He-3/people
Moon to space
Consumables (by-products) Launch Frequency

Flight/Delivery Risk
Early Apollo belt
Other regions
EXPLORATION AND MINE PLANNING

Concepts are similar to large tonnage mineral sands dredging
Millions of tons/yr. of low grade material
Grade distribution/variation
Drill and sample operations
Large crater distribution
Large boulder distribution
Mine location
Determined by access to adequate reserves over time at maximum grade with minimum of impediments to mining
Dump/tailings sites (if other than behind the miner)

MINING

Concepts are similar to large tonnage mineral sands mining operations.

Mining Equipment
Million tonnes/yr.
Reliability/low maintenance/automation
Equipment mass (stability during mining)
Low Temperature (-50 C.) operation at mining face

Mining/Beneficiation/Processing
Combined/tandem/separated
Human presence requirements

Mine Plan
Operational Cycle Limitations
Power/maintenance/processing capacity
Large Boulders
Sensing/removal

Mining Support Base
Fixed/semimobile/mobile

Pilot Plant and Reserve Delineation
May be undertaken in conjunction with early base for O2 production for space transportation (see scenario of Schmitt, 1988, for example).
BENEFICIATION

Concepts are related to mineral sand beneficiation. Initial separation of He-3 rich and He-3 poor material.

- Attritioning, grinding
- Screens, vibrators, material handling, and evolved gas

Preparation for Concentration of Retort Feed

- Grain size vs. electrostatic and/or magnetic susceptibility
- Middlings circuits

Concentration of retort feed

- Middlings circuit

Retort Extraction of gases

- Thermal power (solar vs. nuclear)/corrosion control/
  loss control (surface area about 0.5 m²/gm)
- Excitation (sonic, microwave)

Transport of gases to processing plant vs. transport of retort feed to combined beneficiation and processing plant

PROCESSING

Concepts similar to Hg ore and oil shale processing and crude oil refining.

- Thermal Power
  - Solar/Nuclear
- Corrosion Control
- Heat recovery
- Condensation and separation of products
  - Radiator size
  - Lunar night operation
  - He-3 separation on moon or on Earth
- Storage
  - Liquefaction of H₂ and He
- Operational Cycle Limitations
  - Power/maintenance/mining and benefication capacity
SUPPORT

Concepts similar to North Slope crude oil production support
Lunar base services
   Habitat/food/landing and launch services/health maintenance/
   recreation/consumables production
Earth to Moon logistics
   Spares/new construction/personnel replacement and additions
Moon to Earth Logistics
Moon to Space Logistics
   Consumables export
Other Tenant services
   Science
   Propellant supply
   Food production
   Special site preparation (radioteloscope,mass drivers,
   habitats)
   Settlement utilities and services (company town)
Possible tenant interactions
   Public order
   Lunar atmosphere
   Seismic noise

FINANCIAL

D/He-3 fusion development and lunar He-3 mining development must
proceed in parallel

Management Organization
Operating Plan
Capital Acquisition and Cost
Budgeting
Product Pricing
Marketing
Margins controls
Personnel
Training
Inventory Management
Imports (reliability of supply)
Exports (reliability of supply)
Discards
Purchasing
R & D and Exploration
Environmental Control
Economies of Scale
Energy Pay-back
Price of competitive energy sources

CONCLUSIONS

1. Concepts that relate to economic geology of recovering He-3 from the lunar maria are not new to human experience.

   Space Operations
   Lunar Operations
   Large tonnage mining
   Beneficiation of low grade detrital resources
   Processing by thermal methods
   Logistical support of large scale commercial and scientific operations in remote locations
   Financial support and management of large scale commercial operations

2. A parametric cost and technology evaluation scheme, based on existing and future data, is required to qualitatively and quantitatively assess the comprehensive economic feasibility and Return on Investment of He-3 recovery from the lunar maria.

   Early outputs from this evaluation should include:
   A. Candidate mining sites based on existing data
   B. Additional earth-based studies and data acquisition required to further evaluate the candidate sites.
   C. Types of data from additional automated or human exploration required to further evaluate the candidate sites.
D. Types of data from engineering, financial, and mission planning activities required to further evaluate economic feasibility and ROI of lunar He-3 recovery.

E. Detailed scenarios for the initiation and operation of a lunar base or settlement for He-3 production.

3. Detailed plans for the research, development, and construction leading to commercial use of D/He-3 fusion technology are required in order to assess the economic, societal, and political value of He-3 supplies from the moon.

POLITICAL CONCLUSIONS

1. D/He-3 fusion and lunar He-3 mining will not become commercially viable or politically assured without the active and politically visible participation of large numbers of interested voters (2–3000 per Congressional District) who support a "second to none" U.S. presence in space. A private sector effort should be organized for this purpose.

2. International cooperation, if any, should be based on user interests (such as the INTERLUNE concept described by Schmitt, 1988) rather than on one nation/one vote interests. Law of the sea/Moon Treaty international regimes should be avoided in order to not delay resource related activities indefinitely.

3. Interagency cooperation (NASA, DOE, etc.) should be based on each agency's specific and long term commitment of both funds and personnel slots to a joint management team.

4. Informal coordination and discussion between all interested parties should continue to be encouraged and facilitated by NASA as has been done so well at this workshop.

REFERENCES


