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**N89 - 14849**

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**ECONOMIC GEOLOGY OF LUNAR HELIUM-3**

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## PREFACE

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 than 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/km<sup>2</sup> 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 O<sub>2</sub>

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  $0.5 \text{ m}^2/\text{gm}$ )

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 H<sub>2</sub> and He

Operational Cycle Limitations

Power/maintenance/mining and beneficiation 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 (radiotelescope, 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.

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