Design of a Heat Exchanger for the Extraction of Lunar Solar Wind Volatiles

The Greatbatch Foundation
The Grainger Foundation

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Introduction and Background

Fusion reactors using helium-3 could produce nuclear power without radioactive waste

Homer IEC device and FTI Director Dr. Gerald Kulcinski

Progress has been made toward ^{3}He Fusion Reactors at the UW FTI IEC lab

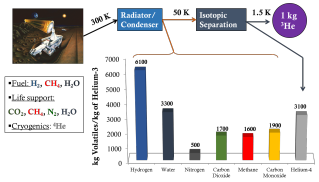
Helium-3 and other volatiles have been embedded into the lunar regolith

- Lunar ^{3}He concentration measured in Apollo 11, 12, 14, 15, 16, & 17 plus USSR Luna 16 & 20 samples.
- Average of ~10 ppb ^{3}He concentration measured in mare regolith
- 20 ppb is the predicted actual value due to agitation losses prior to thermal evolution
- Analysis, published in 1986, indicates that >10^8 kg of ^{3}He exists near the lunar surface
- In a reactor, 1 kg of ^{3}He could produce 10 MWe-y
- 10^8 kg could equal >1000 years of world energy supply.
- There is 10 times more energy in the ^{3}He on the Moon than in all of today's economically recoverable coal, oil, and natural gas on the Earth
- ~40 tonnes of ^{3}He would supply the entire 2014 US electricity needs.

The sources of helium-3 on the Earth would not support its use in the energy industry

- Atmosphere: helium-3 concentration in atmosphere is ≈ 7x10^{-12} by volume. The total amount in the entire atmosphere is ≈ 4,000 tonnes
- Natural Gas: potentially as much as 280 kg in reserves and speculative sources that are not being tapped
- Decay of Tritium: tritium decays into helium-3 with a 12.3 year half life and 2-4 kg/yr of helium-3 is produced from tritium in the U.S. and Canada
- Increased Usage: supply depleted of helium-3 from tritium decay (down to < 10 kg in the U.S. as of 2010)
- Increased Price: from (~$1,000,000/kg) to (> $30,000,000/kg)
- Available for Fusion R&D: only ~10 kg ^{3}He (200 MW-y fusion energy) is accessible on Earth

Tonnes of other volatiles could be collected per kg of ^{3}He



Results from Apollo 11 sample 10086.16

^{3}He extraction (kg/yr)	66*
Mining time (hr/yr): *90 % of lunar days*	3942
Excavation rate (tonnes/hr)	1258
Processing rate (tonnes/hr)	556**
Excavation depth (m)	3.0
Area excavated (km²)	1.0

*assuming a 20ppb ^{3}He grade (10ppb was used by Sviatoslavsky and Gajda for ^{3}He at 33 kg/yr)
** only 44% of mined material is processed

Thermal process power (MW)	12.3
Operating power (M-I, M-III) (kWe)	200, 350
Miner mass (M-II, M-III) (tonnes)	18, 9.9

TAKRAF SRs 8000 bucket-wheel excavator can excavate > 16,000 tonnes/hr of coal and has a service mass of 14,200 tonnes

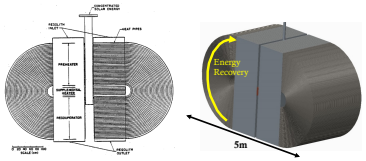
Mark II and III lunar helium-3 miner parameters

Three FTI lunar ^{3}He miner designs have been developed

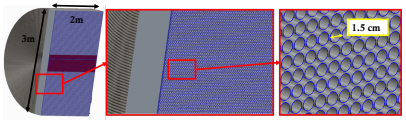
Mark I, II, and III lunar helium-3 miners

Methodology and Analysis

The heating system minimizes thermal power use by recovering heat from processed regolith via evaporation and condensation within heat pipes



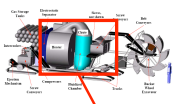
Mark series lunar miner regolith heating system



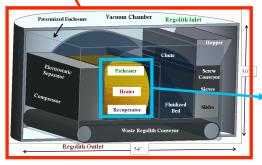
Mark series lunar miner regolith heating system zoom in view to individual heat pipes

- 85% energy recovery by using heat pipes
- 12.3 MW from solar collector instead of 82 MW
- Heats 157 kg/s of regolith from 30 °C up to 700 °C to release 85% of embedded ^{3}He
- Evolves 16.7 g/hr of ^{3}He (66 kg in 3942 hours of mining)

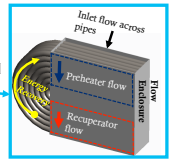
The Helium Extraction and Acquisition Test bed (HEAT) will be a scaled down prototype of the full scale regolith heating and processing system



- 1:1000 scale mass flow rate (0.157 kg/s)
- Corresponds to ~ 1.3 tonne/hr mining rate
- Design for <100 μm JSC-1A regolith simulant
- Counter flow heat exchanger configuration
- Approximately isothermal heat pipes



Helium Extraction and Acquisition Test bed (HEAT)



Heat pipe heat exchanger component of HEAT

- Working fluid – heat pipe material combinations
  - Water in copper pipes: operating up to ~250 °C
  - Mercury in stainless steel pipes: operating between 250- 500 °C
  - Sodium and or potassium in stainless steel pipes: operating above 500 °C

Heat Transfer Relations

NTU-Effectiveness Relations

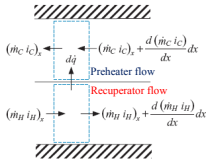
$$NTU(\text{counter flow}) = \frac{\varepsilon}{1-\varepsilon} \qquad NTU = \frac{UA}{C}$$

Total Thermal Resistance

$$(UA)^{-1} = R_{tot} = \left(\frac{1}{hA_{pre}}\right) + \left(\frac{1}{hA_{rec}}\right) = \frac{2}{hA}$$

Convection Correlation (Dietus Boelter)

$$Nu = 0.023 Re^{4/5} Pr^{2/5} = \frac{hD_h}{K}$$



Counter flow heat exchanger heat transfer model

Flow Relations

Reynolds #

$$Re = \frac{\rho U_{avg} D_h}{\mu}$$

Prandtl #

$$Pr = \frac{C_p \mu}{K}$$

Hydraulic diameter

$$D_h = \frac{2\delta L_{pipe}}{\delta + L_{pipe}}$$

Pressure drop per length

$$\left(\frac{dP}{dz}\right) = \frac{\rho g H_{pre}}{L_{eff}}$$

Capillary Flow Model

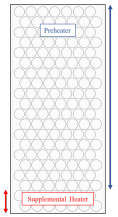
$$\dot{m} = \rho U_{avg} A_{avg} = \frac{\pi \rho D_h^4}{128\mu}\left(\frac{dP}{dz}\right)$$

Results

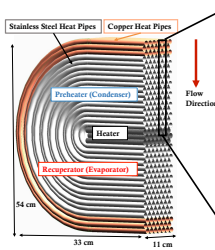
Optimization (minimization of mass) of the heat pipe quantity and arrangement led to a design that was then simulated with a computational fluid dynamic code (Fluent). Physical regolith simulant flow tests will further refine the design.

Heat pipes	119
Columns	7
Rows	17
Pipe outer diameter	1.5 cm
Pipe heat exchanging length	22.3 cm
Heater rows	3
Distance between pipe columns	1 mm
Heat exchanger mass	6 kg
Heat exchanger height	54 cm
Heat exchanger width	10.7 cm

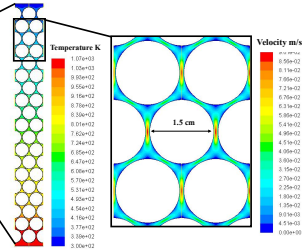
HEAT heat pipe heat exchanger geometry and mass



Cross section of heat pipe arrangement

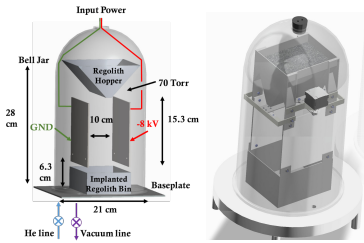


HEAT heat pipe heat exchanger CAD model



Regolith temperature evolution and velocity magnitude contours through heat pipe matrix

Helium will be implanted into regolith simulant for use in the HEAT system. The preliminary implantation system uses a dc glow discharge between parallel plates. The simulant would fall through the discharge for implantation



Implantation system concept (left) and preliminary CAD model (right)

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