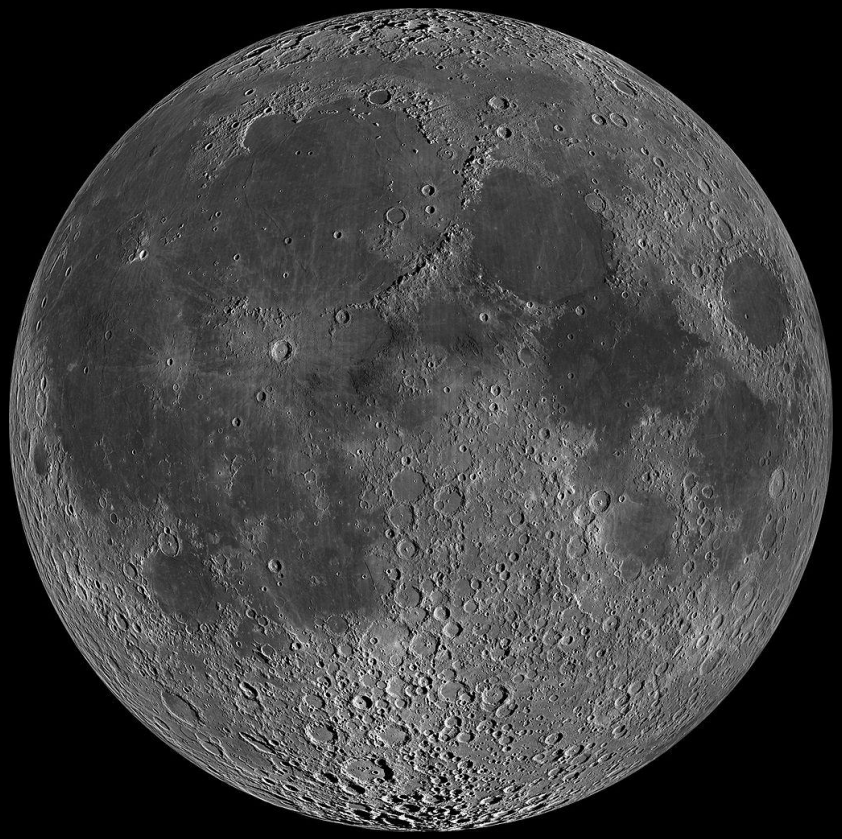
Path Toward a Scalable Lunar Volatiles Miner Prototype

National Council of Space Grant Directors' Fall Meeting



Charleston,SC
10/14/2013

Aaron D.S. Olson

Fusion Technology Institute, University of Wisconsin-Madison

Outline

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- Uses of Lunar Volatiles
  - Helium-3 Fusion
  - Life Support Volatiles
- Lunar Volatiles Miner Designs
  - Operation of the Mark-III
- Development Path
- The Mark IV Miner Objectives

Helium-3 Enables Clean Nuclear Fusion

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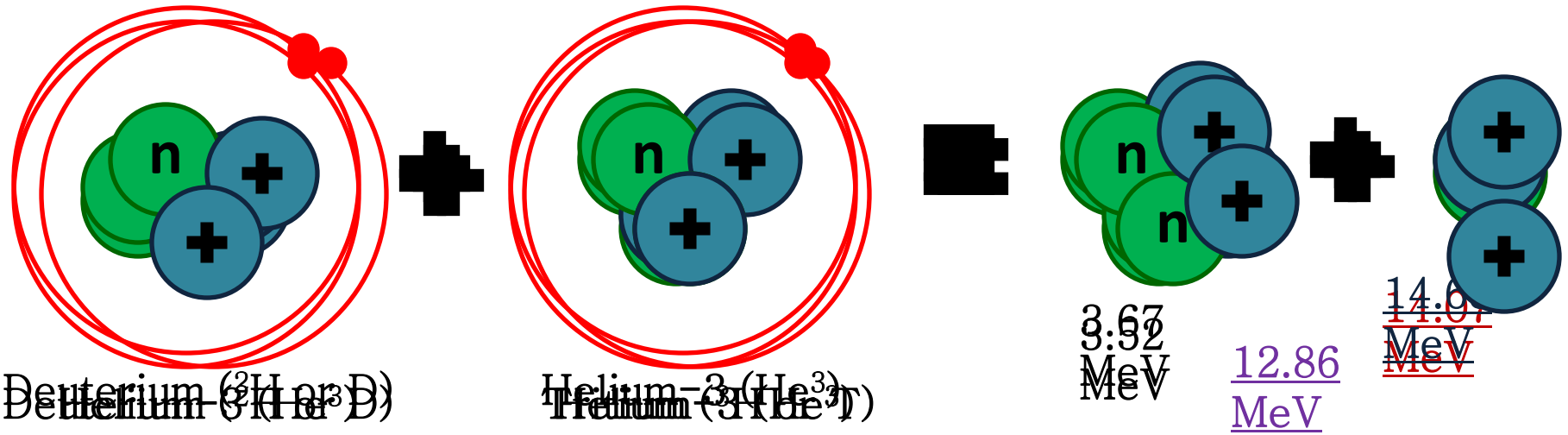
Contrast of some key nuclear fusion reactions

Output energy mostly from protons, some neutrons are still produced in side D-D reactions

No neutrons, Nuclear Power Without Radioactive Waste!

High energy neutrons: radioactive waste and reactor wall issues



Deuterium (^2H or D)

Helium-3 (He^3)

D^3He and $^3He^3He$ Fusion Cycles Have Been Demonstrated in a Fusion Technology Institute Lab

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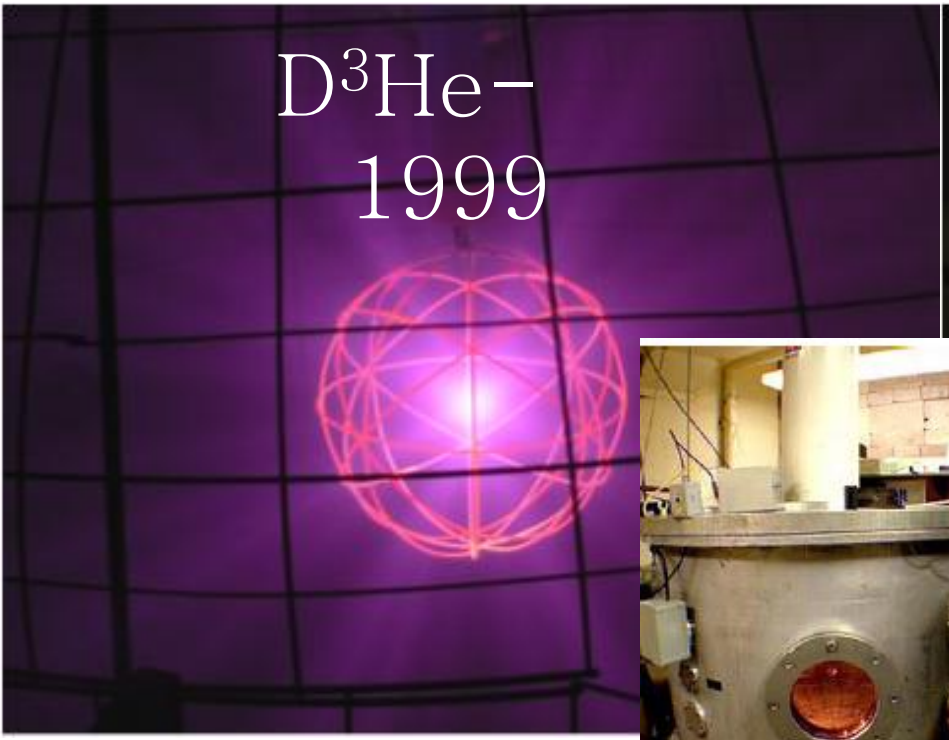

Terrestrial Helium-3 Resources

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Three main sources of Helium-3 on the Earth

Atmosphere:
Helium-3 concentration in atmosphere is ≈ 7×10^{-12} by volume.
Total in the entire atmosphere is ≈ 4,000 metric 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 after 12.3 years, about 1 kg/yr of Helium-3 is produced

Shortage: increased usage in the last decade has nearly depleted the supply of Helium-3 from Tritium decay (down to < 10 kg as of 2010)
Also drove price from (~$1,000,000/kg) to (> $7,000,000/kg)

The Solar Wind Volatiles

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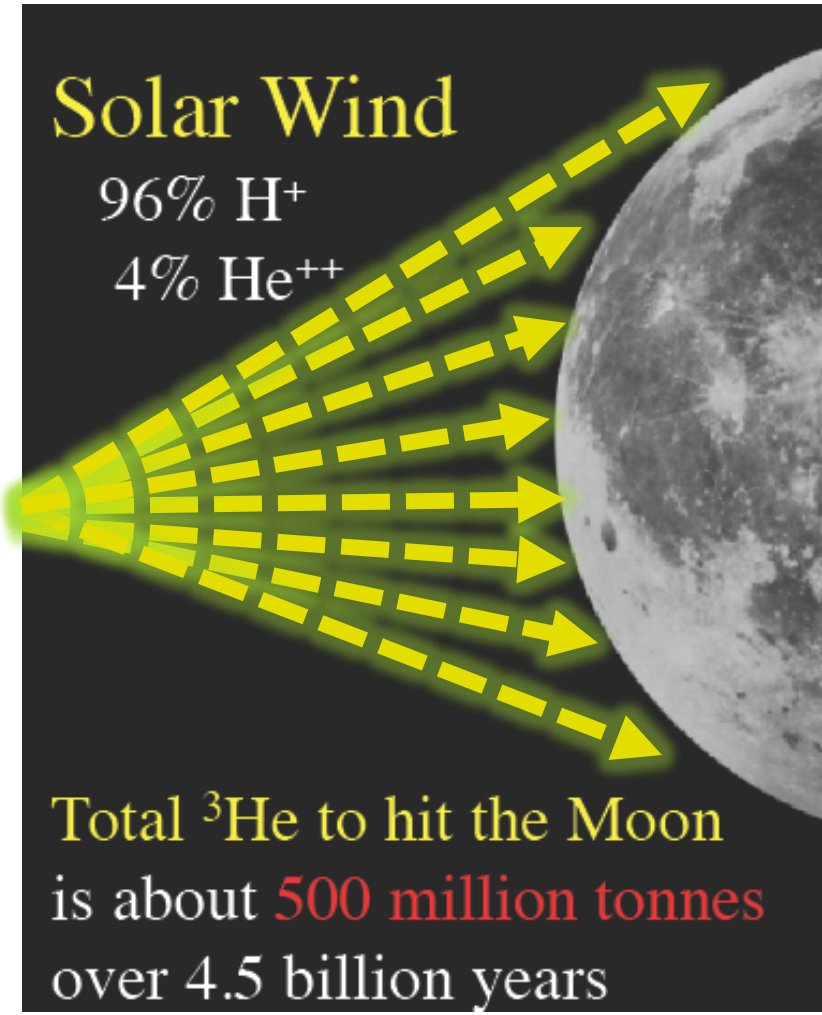
Ionized solar wind is deflected by the Earth's Magnetosphere

Composition : Mostly Hydrogen
- Biogenic elements: H, C, N
- Noble gases: He, Ar, Kr, Xe, Ne

Solar Wing Volatiles (SWV) embedded in top few hundred angstroms

Meteoritic bombardment churns SWV several meters deep into regolith

SWV Retained preferentially in regions with higher Titanium content (Ilmenite: $FeTiO_3$)



Lunar Helium-3 Enables Clean Nuclear Fusion

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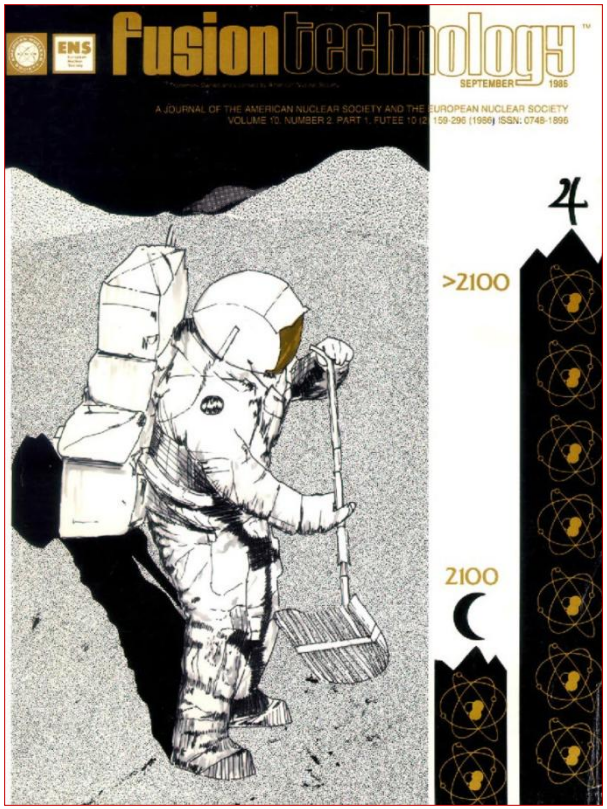
- Lunar ^{3}He concentration measured in Apollo 11, 12, 14, 15, 16, & 17 plus USSR Luna 16 & 20 samples.
- Analysis indicates that ~10^9 kg of ^{3}He exists near the lunar surface, which equals ~1000 years of world energy supply.
- 40 tonnes of ^{3}He would supply the entire 2012 US electricity needs.
- ~10 kg ^{3}He (200 MW-y fusion energy) is accessible on Earth for R&D.
- *A small fraction of the inventory (~10^{23} kg) of ^{3}He in the Solar System's gas giant planets would supply world energy needs for far longer than the age of the universe.*



L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* 10, 167 (1986).

^{3}He Mining Produces Valuable Volatile By-Products

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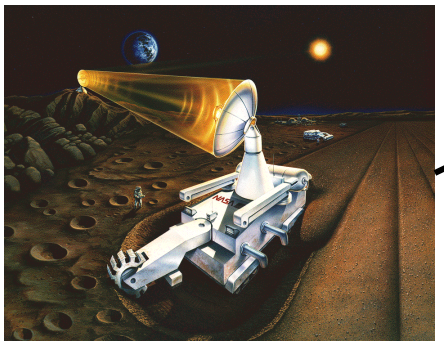
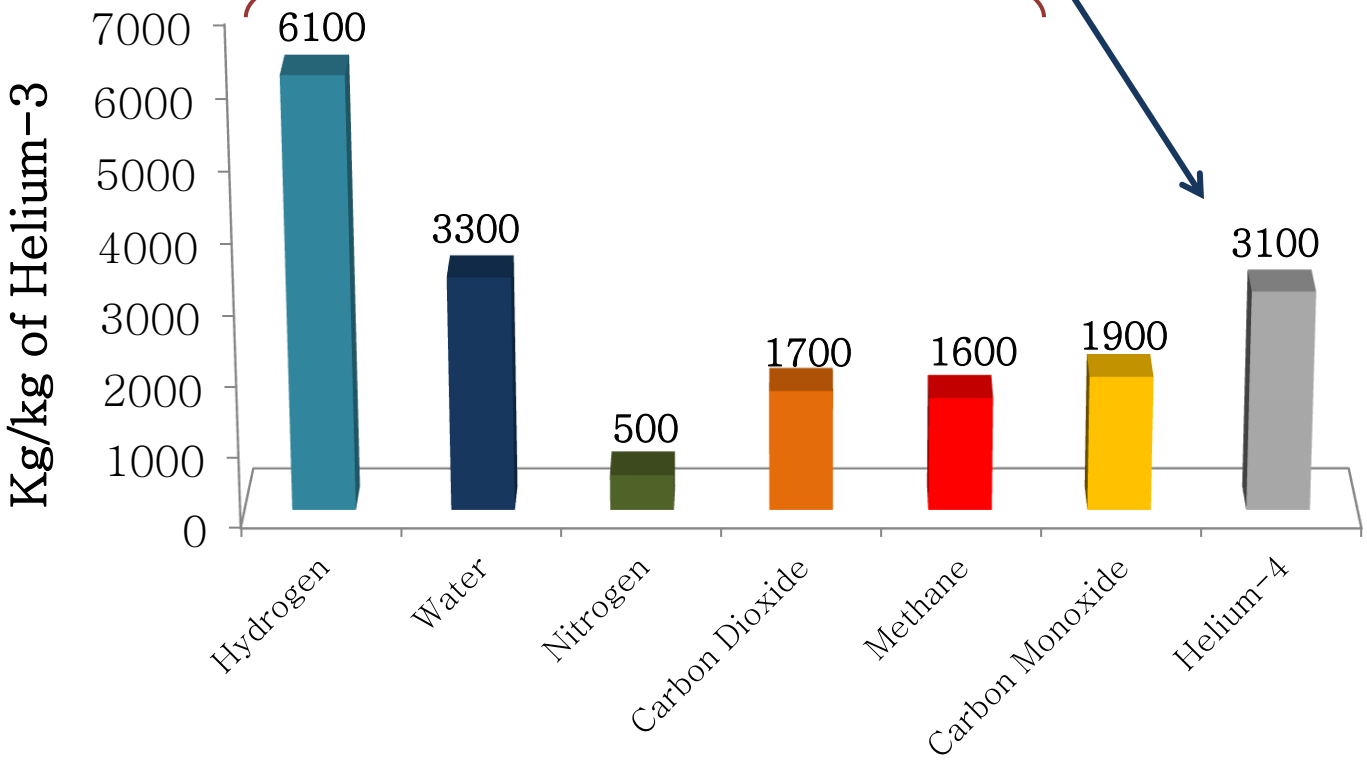


300 K → Radiator/ Condense → 50 K → Isotopic Separation → 1.5 K → 1 kg ^{3}He

- Fuel: H_2, CH_4, H_2O
- Life support: CO_2, CH_4, N_2, H_2O
- Cryogenics: ^{4}He



Three Wisconsin Lunar ^{3}He Miner Designs Completed

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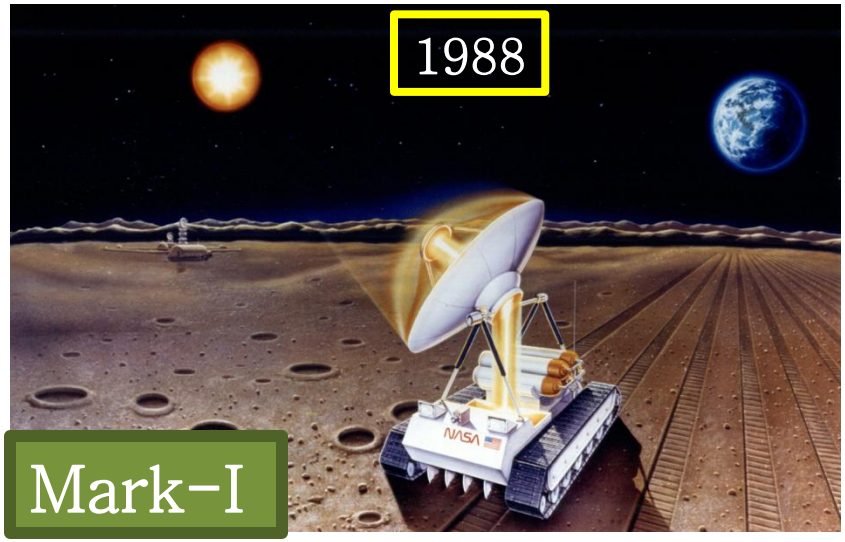

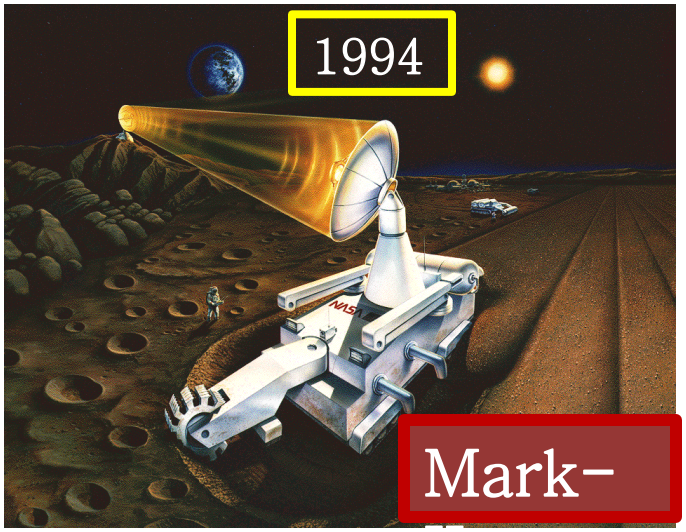

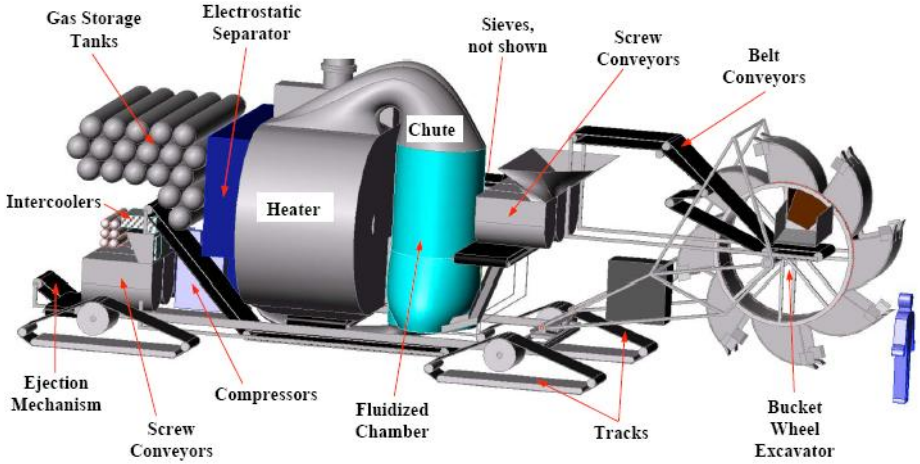

*Enclosure, solar collector, and RF rectenna not shown

2006
Mark-

Regolith Processing in the Mark III Miner

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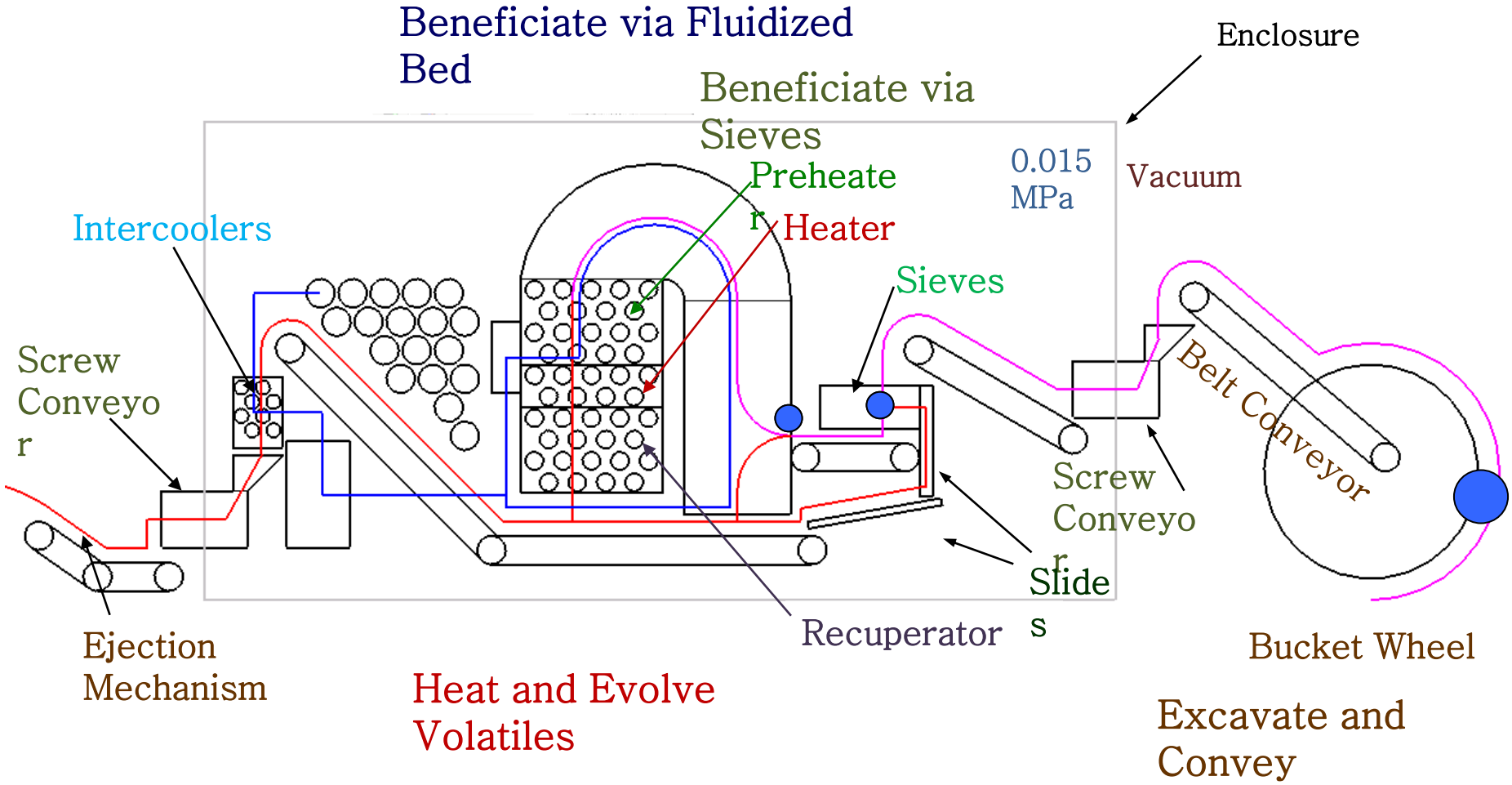

Volatile Flow and Collection Schematic

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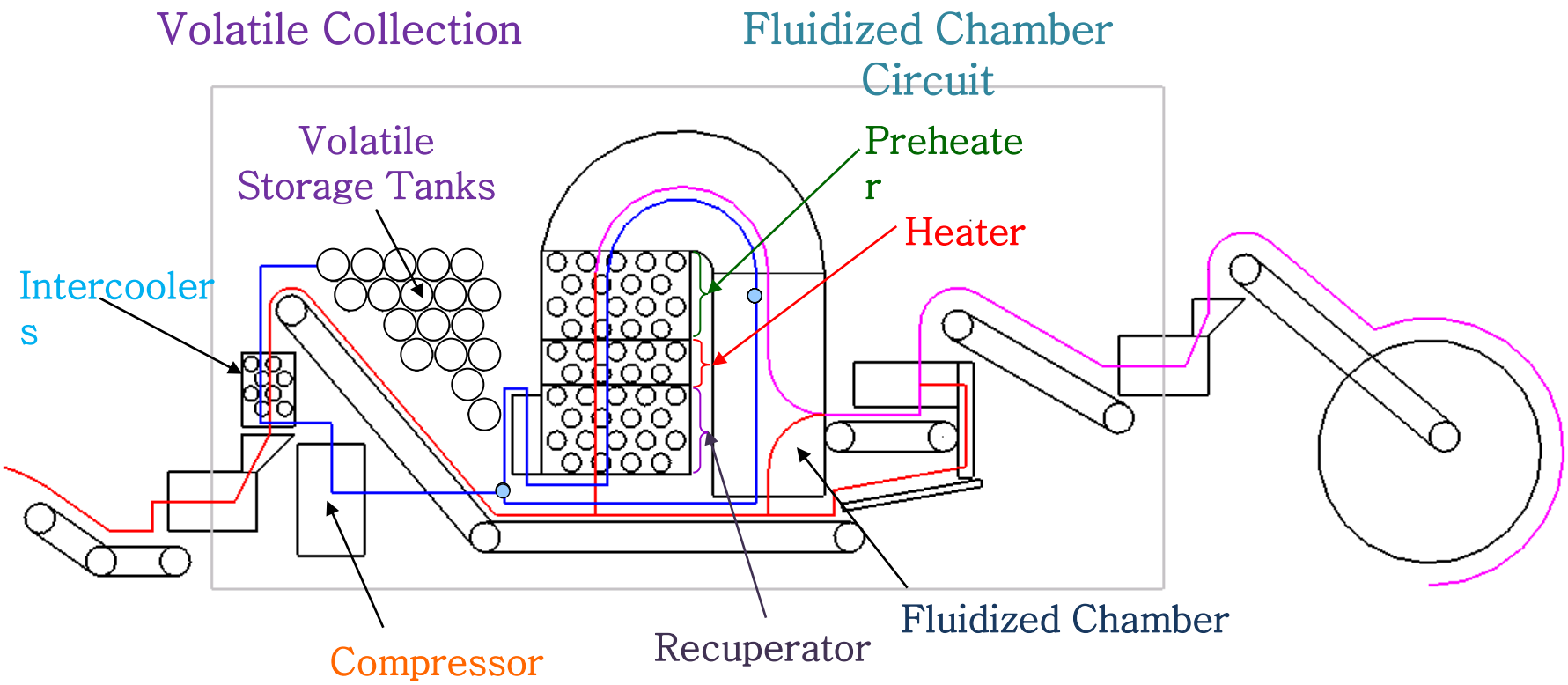

Mark-3 Operational Parameters, Mass and Power Distributions

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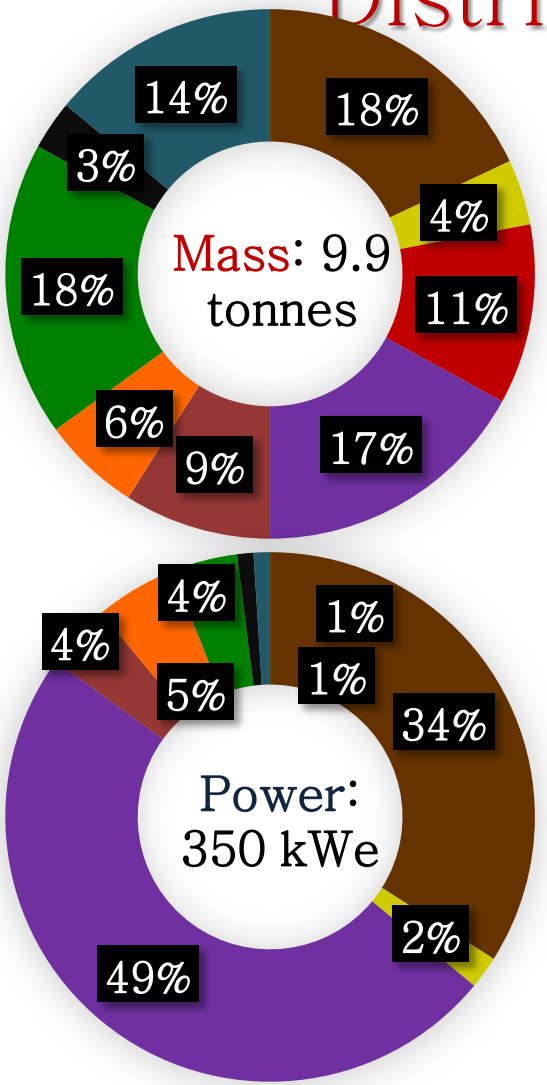

Selected Annual Miner Parameters	
^{3}He extraction (kg)	66*
Mining time (hr): *90 % of lunar days*	3942
Excavation rate (tonnes/hr)	1258
Processing rate (tonnes/hr)	556
Excavation depth (m)	3.0
Forward miner speed (m/hr)	23
Area excavated (km^2)	1.0
Thermal process power (MW)	12.3
Operating power (M-II, M-III) (kWe)	200, 350
Miner mass (M-II, M-III) (tonnes)	18, 9.9

*assuming a 20ppb ^{3}He grade, however only 10ppb was used by Sviatoslavsky and Gajda in their miner designs leading to reported annual acquisition of ^{3}He at 33 kg

Potential Lunar Mining Roadmap

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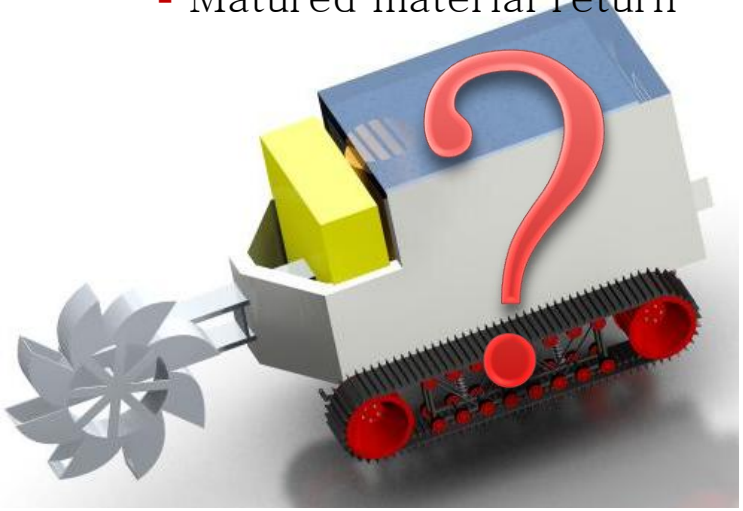
Ground Truth ~2013–2020

- No surface assets
- Limited landing capability
- Limited material return

(NASA RESOLVE)

Demo and Small Scale ~2020–2030

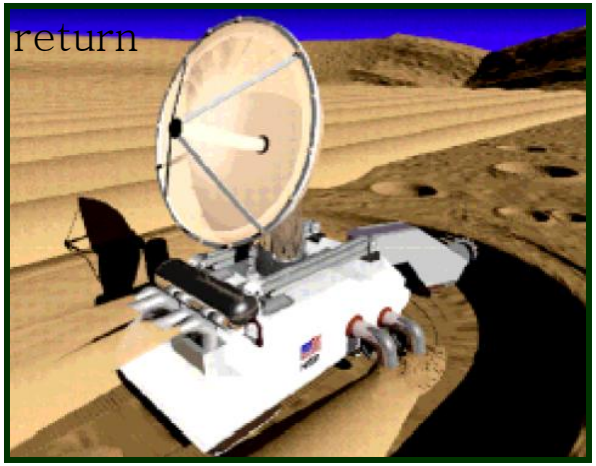
- Limited surface assets
- Matured landing capability
- Matured material return



(Demonstration scale concept)

Industrial Mining ~Post 2030

- Matured surface assets
- Advanced landing capability
- Advanced material return



(UW Mark-II concept)

Mining for Solar Wind Volatiles Could Provide Life Support for 333 People

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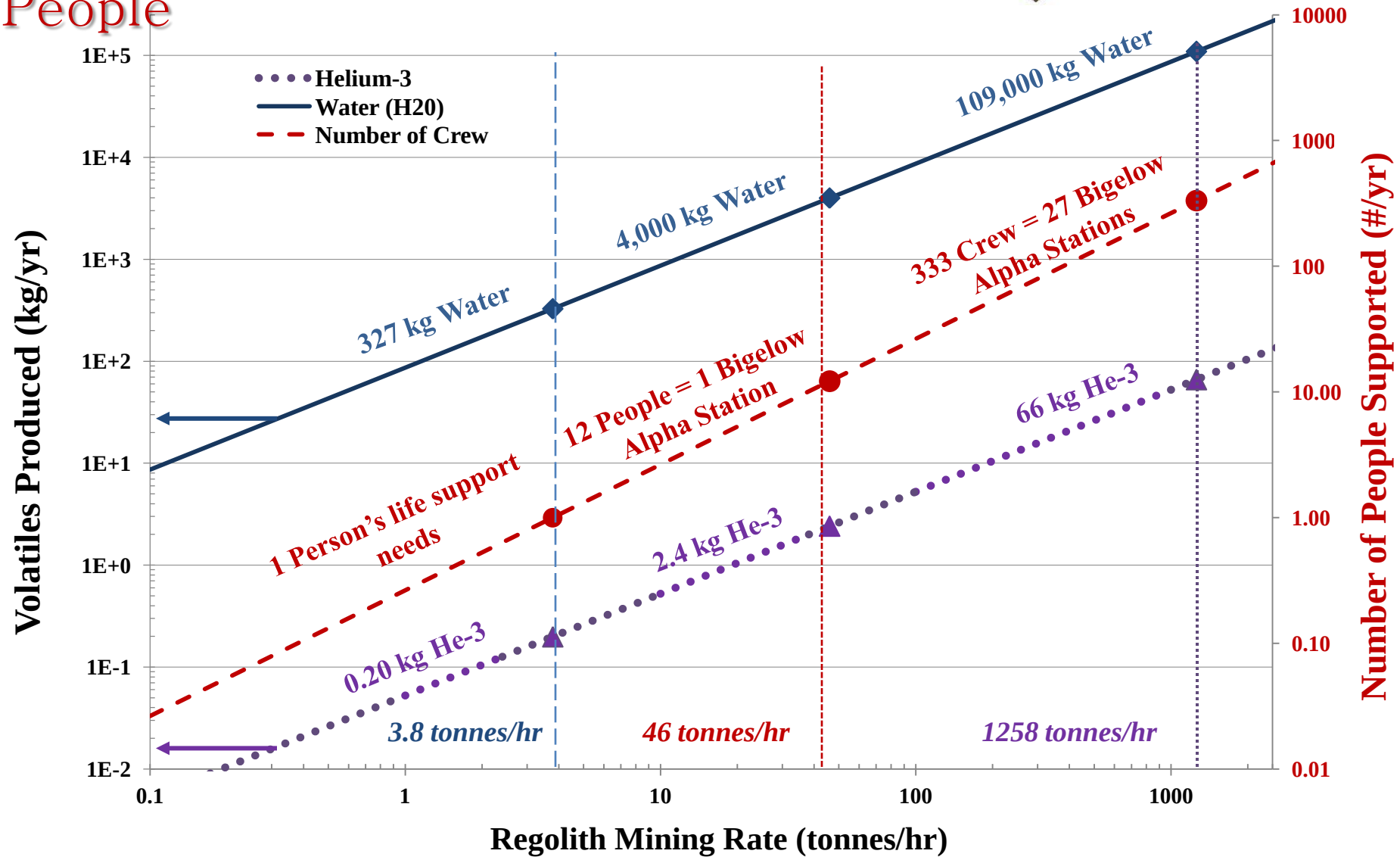

International Civil Agencies and New Space Companies are Developing Lunar Capabilities

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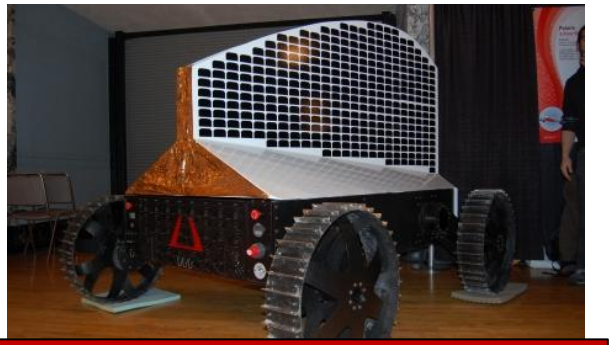
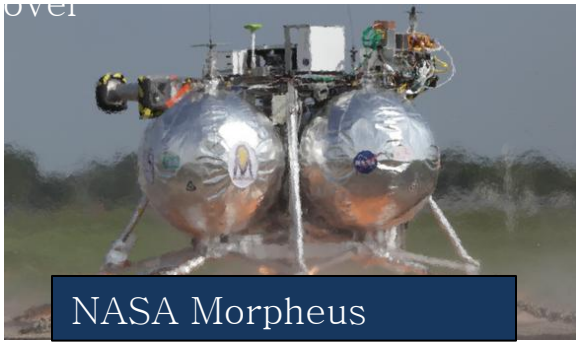
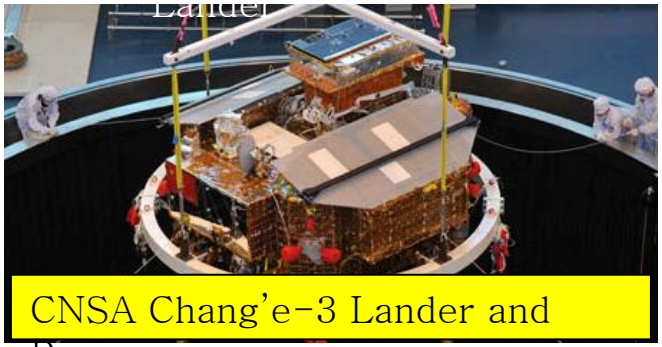
- **NASA:** Resource Prospector, Lunabotics, Morpheus lander
- **CNSA:** Chang'e 3,4…
- **ISRO:** Chandrayaan-2
- **Roscosmos:** Luna 25,26…
- **JAXA:** SELENE 2,3…
- **Google Lunar X-Prize**
- **20 proposed lunar missions** (2013-21)



Astrobotic Technologies Polaris



NASA Morpheus



CNSA Chang'e-3 Lander and Rover

Mark-IV: The First ^{3}He and Volatiles Miner Prototype

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Objectives of the Mark-IV Miner Prototype

- Demonstrate ^{3}He extraction process
- Produce volatiles for life support and other in-space needs
  - O_2, H_2O, H_2, ^{4}He, N_2, CO_2,CO, CH_4
- Scalable to meet lunar exploration and space development needs prior to operational ^{3}He fusion power plants

They Said It Couldn't be Done

Upcoming Lunar ^{3}He Fusion Book

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Follow-on to *Return to the Moon* by Dr. Harrison Schmitt

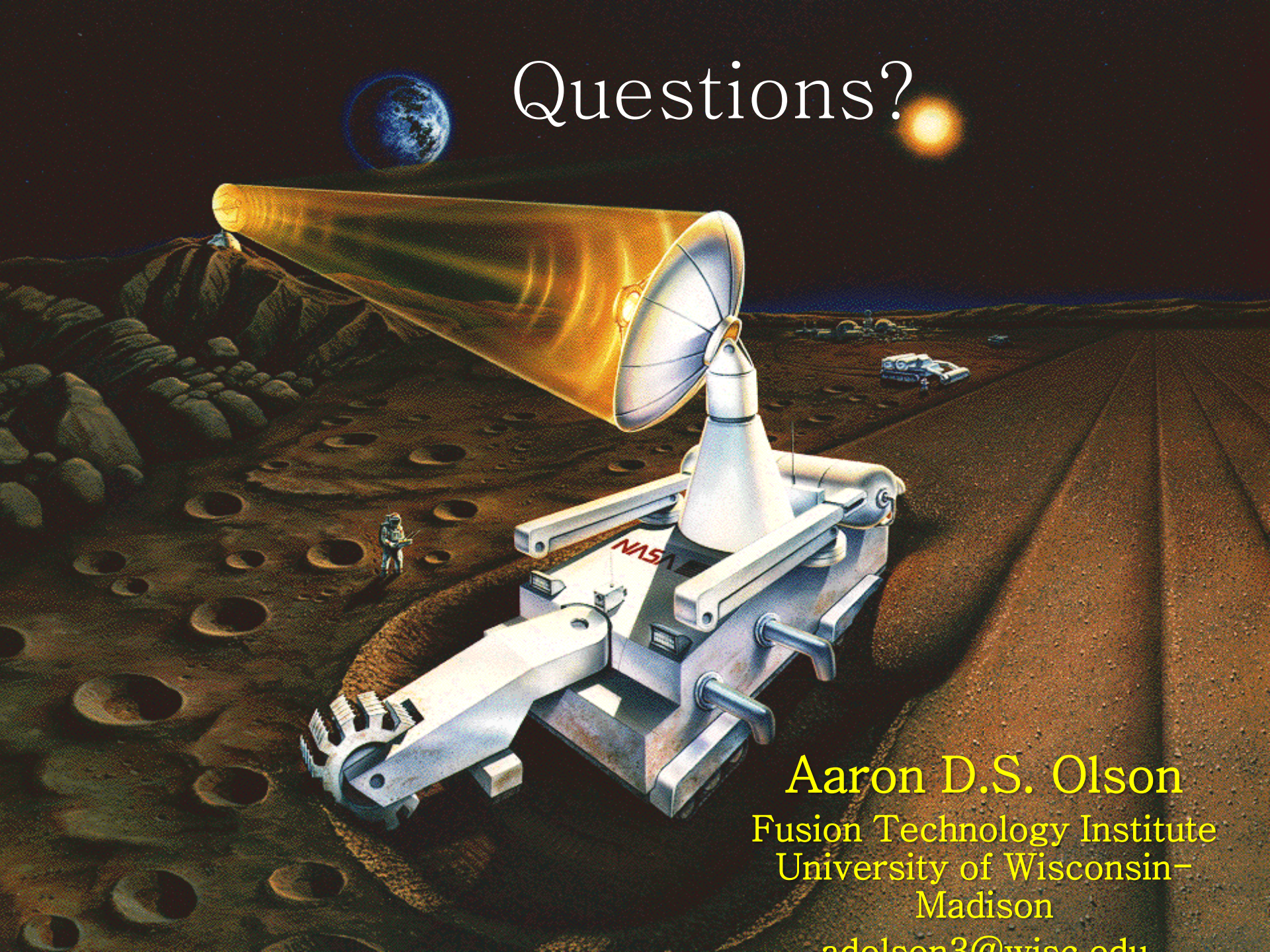
Discusses

- Increasing need for power worldwide
- Potential role of ^{3}He Fusion technology
- Lunar Bases and Resources
- Legal Regimes for Lunar Mining
- Economics of ^{3}He Procurement
- Space Applications of ^{3}He Fusion
- Current Lunar Initiatives

Authors: Dr. Harrison Schmitt, Dr. Gerald Kulcinski, Dr. John Santarius, Aaron Olson

Thank you Wisconsin Space Grant Consortium!

Questions?



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Mining Maria Regolith Could Provid Life Support to Crews in Space

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Volatiles Delivered to ISS in 2012*		
Volatile	Mass (kg)	Mass/crew member (kg) #
Air	38	6.3
Nitrogen^	30	5.0
Oxygen	253	42.2
Water	1965	327.5

*8 Cargo resupply missions conducted by: the Russian Progress, European ATV, Japanese HTV and Space-X Dragon

^ Assumes ~78% N_2 air composition

6 Crew more or less constant in 2012

Products of Heating Mare Regolith to 700 °C		
Volatile	Mass evolved per tonne of regolith mined (g)**	Mass evolved per kg of ^3He evolved (kg)
H_2	43	6100
^4He	22	3100
^3He	0.007	1
H_2O	23	3300
N_2	4.0	500
CH_4	11	1600
CO	13.5	1900
CO_2	12	1700

**After beneficiation, 450 kg of regolith is heated

- Delivered Oxygen is not equal to the metabolic requirement of 0.84 kg O_2/day
  - 0.84 kg Oxygen is for the average adult American male
  - Water is electrolyzed on board for Oxygen production
- Delivered water is not equal to the requirement of 3.9 kg H_2O/crew member per day
  - ECLSS water recycling system (urine filtration)

Schematic of the Mark III Miner

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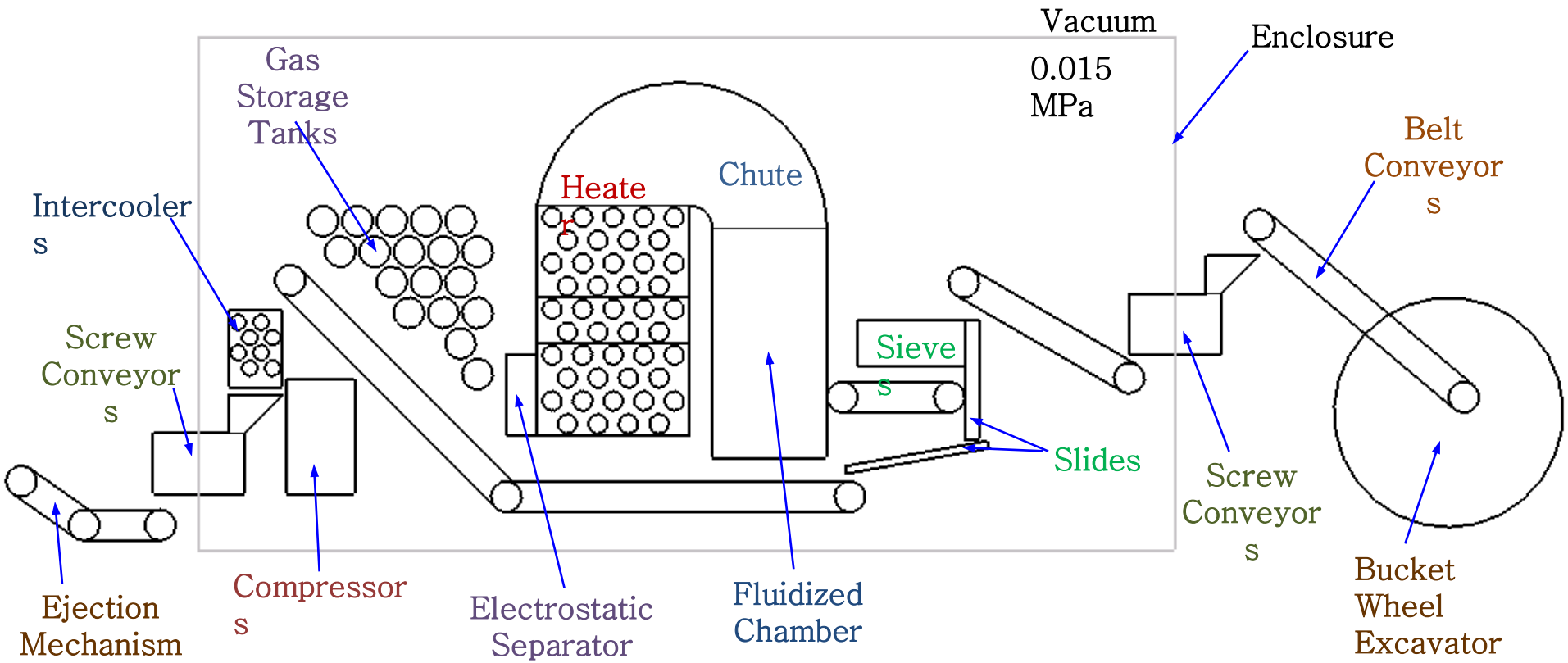
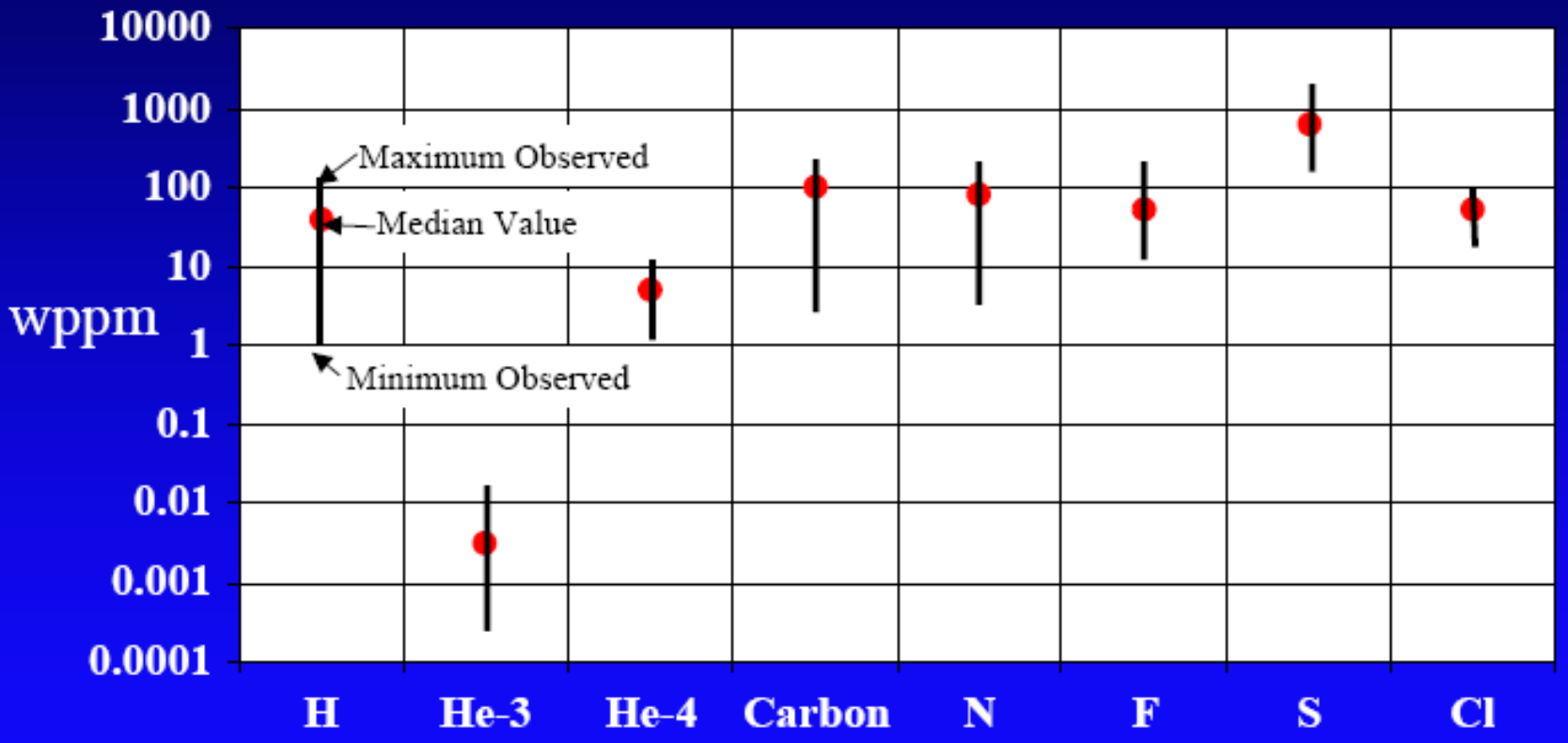
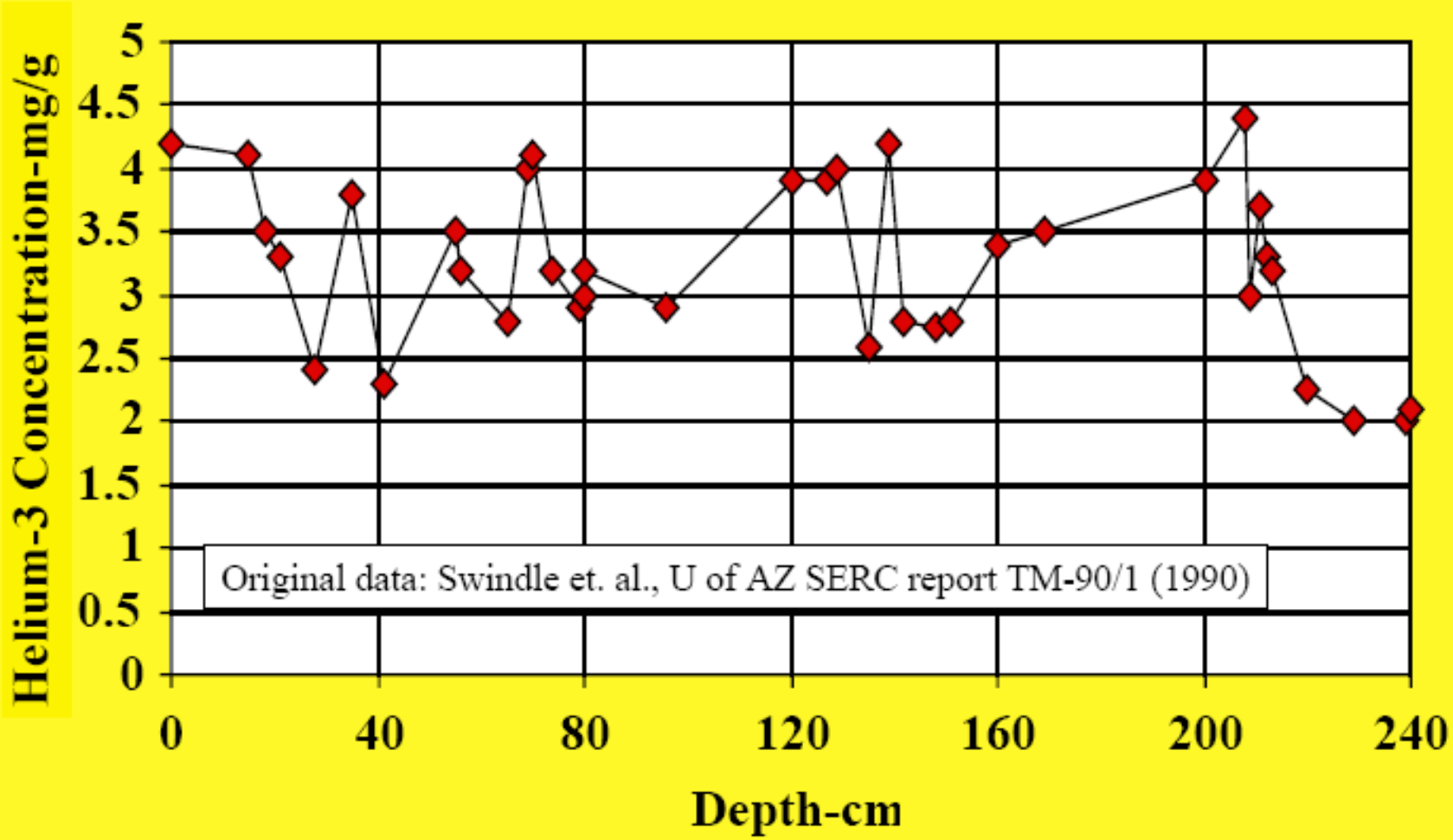


The Concentration of Lunar Volatiles in the Apollo Soil Samples Covers a Wide Range of Values



The Concentration of ^{3}He in Apollo-15 Drill Core Samples Remains Reasonably Constant With Depth



Researching Lunar Volatiles Mining

Advisor: Dr. Gerald Kulcinski FTI Director